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January 2005 • NREL/SR-500-36345

Design and Experimental Results for the S827 Airfoil

Period of Performance: 1998 – 1999

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ABSTRACT

A 21-percent-thick, natural-laminar-flow airfoil, the S827, for the 75-percent blade radial station of 40- to 50-meter, stall-regulated, horizontal-axis wind turbines has been designed and analyzed theoretically and verified experimentally in the NASA Langley Low-Turbulence Pressure Tunnel. The primary objective of restrained maximum lift has not been achieved, although the maximum lift is relatively insensitive to roughness, which meets the design goal. The airfoil exhibits a relatively docile stall, which meets the design goal. The primary objective of low profile drag has been achieved. The constraints on the pitching moment and the airfoil thickness have been satisfied. Comparisons of the theoretical and experimental results generally show good agreement with the exception of maximum lift, which is significantly underpredicted.

INTRODUCTION

The majority of the airfoils in use on horizontal-axis wind turbines today were originally developed for aircraft. The design requirements for these airfoils, primarily National Advisory Committee for Aeronautics (NACA) and National Aeronautics and Space Administration (NASA) airfoils (refs. 1–6), are significantly different from those for wind-turbine airfoils (ref. 7). Accordingly, several families of airfoils have been designed specifically for horizontal-axis wind-turbine applications, as shown in the following table.

Diameter	Type	Thickness Category	Airfoil			Reference
			Primary	Tip	Root	
2–10 m	Variable speed Variable pitch	Thick	—	S822	S823	13
10–20 m	Variable speed Variable pitch	Thin	S801	S802 S803	S804	8
	Stall regulated	Thin	S805 S805A	S806 S806A	S807 S808	8
	Stall regulated	Thick	S819	S820	S821	12
20–30 m	Stall regulated	Thick	S809	S810	S811	9
	Stall regulated	Thick	S812	S813	S814 S815	9 and 10
20–40 m	Variable speed Variable pitch	—	S825	S826	S814 S815	10 and 14
30–50 m	Stall regulated	Thick	S816	S817	S818	11
40–50 m	Stall regulated	Thick	S827	S828	S818	11 and 15

An overview of all these airfoil families is given in reference 16.

The airfoil designed under the present study is intended for the primary (75-percent) blade radial station of 40- to 50-meter, stall-regulated, horizontal-axis wind turbines. To complement the design effort (ref. 15), an investigation was conducted in the NASA Langley Low-Turbulence Pressure Tunnel (LTPT) (refs. 17 and 18) to obtain the basic, low-speed, two-dimensional aerodynamic characteristics of the airfoil. The results have been compared with predictions from the method of references 19 and 20.

The specific tasks performed under this study are described in National Renewable Energy Laboratory (NREL) Subcontract Numbers AAF-4-14289-01 and AAM-8-17232-01. The design specifications for the airfoil are outlined in the first subcontract's Statement of Work. These specifications were later refined during discussions with James L. Tangler of NREL.

SYMBOLS

Values are given in both SI and U.S. Customary Units. Measurements and calculations were made in U.S. Customary Units.

C_p pressure coefficient, $\frac{p_l - p_\infty}{q_\infty}$

c airfoil chord, mm (in.)

c_c section chord-force coefficient, $\oint C_p \, d\left(\frac{z}{c}\right)$

c_d section profile-drag coefficient, $\int_{\text{Wake}} c_d' \, d\left(\frac{h}{c}\right)$

c_d' point drag coefficient (ref. 21)

c_l section lift coefficient, $c_n \cos\alpha - c_c \sin\alpha$

c_m section pitching-moment coefficient about quarter-chord point,

$$-\oint C_p \left(\frac{x}{c} - 0.25\right) d\left(\frac{x}{c}\right) + \oint C_p \left(\frac{z}{c}\right) d\left(\frac{z}{c}\right)$$

c_n section normal-force coefficient, $-\oint C_p \, d\left(\frac{x}{c}\right)$

h	vertical height in wake profile, mm (in.)
L.	lower surface
p	static pressure, Pa (lbf/ft^2)
q	dynamic pressure, Pa (lbf/ft^2)
R	Reynolds number based on free-stream conditions and airfoil chord
S.	boundary-layer separation location, x_S/c
T.	boundary-layer transition location, x_T/c
t	airfoil thickness, mm (in.)
U.	upper surface
x	airfoil abscissa, mm (in.)
y	model span station, $y = 0$ at midspan, mm (in.)
z	airfoil ordinate, mm (in.)
α	angle of attack relative to x-axis, deg
Δc_d	change in uncorrected section profile-drag coefficient, 0.0350/deg
$\Delta c_{l,max}$	change in maximum section lift coefficient due to leading-edge roughness, $-\dfrac{(c_{l,\,max})_{free} - (c_{l,\,max})_{fixed\ or\ rough}}{(c_{l,\,max})_{free}}$, percent

Subscripts:

fixed	transition fixed
free	transition free
l	local point on airfoil
last	last wake measurement
ll	lower limit of low-drag range

max	maximum
min	minimum
rough	rough
S	separation
T	transition
u	uncorrected for wind-tunnel boundary effects
ul	upper limit of low-drag range
0	zero lift
∞	free-stream conditions

Abbreviations:

LTPT	NASA Langley Low-Turbulence Pressure Tunnel
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration

AIRFOIL DESIGN

OBJECTIVES AND CONSTRAINTS

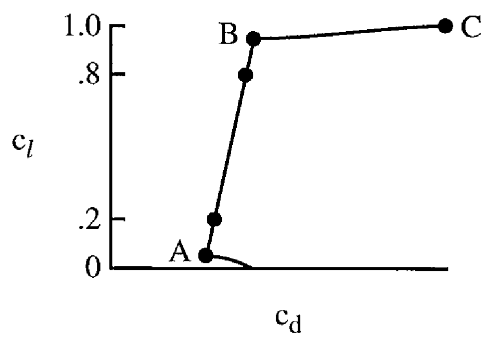
The design specifications for the airfoil are contained in table I. Two primary objectives are evident from the specifications. The first objective is to restrain the maximum lift coefficient to the relatively low value of 1.00 for the corresponding Reynolds number of 4×10^6. A requirement related to this objective is that the maximum lift coefficient not decrease significantly with transition fixed near the leading edge on both surfaces. In addition, the airfoil should exhibit docile stall characteristics. The second objective is to obtain low profile-drag coefficients over the range of lift coefficients from 0.20 to 0.80.

Two major constraints were placed on the design of this airfoil. First, the zero-lift pitching-moment coefficient must be no more negative than –0.07. Second, the airfoil thickness must equal 21-percent chord.

In essence, the specifications for this airfoil are identical to those for the S816 airfoil (ref. 11), except that all the lift coefficients are reduced by 0.20.

PHILOSOPHY

Given the above objectives and constraints, certain characteristics of the design are apparent. The following sketch illustrates a drag polar that meets the goals for this design.

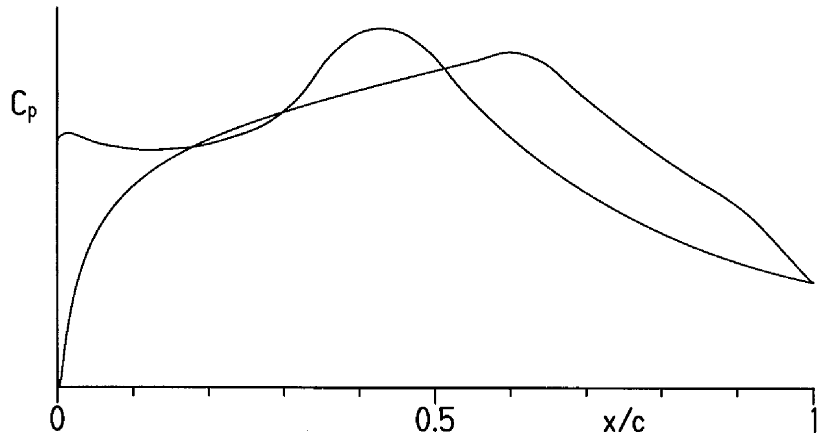


Sketch 1

The desired airfoil shape can be traced to the pressure distributions that occur at the various points in sketch 1. Point A is the lower limit of the low-drag, lift-coefficient range. The lift coefficient at point A is 0.15 lower than the objective specified in table I. The difference is intended as a margin against such contingencies as manufacturing tolerances, operational deviations, three-dimensional effects, and inaccuracies in the theoretical method. A similar margin is also desirable at the upper limit of the low-drag range, point B, although this margin is constrained by the proximity of the upper limit to the maximum lift coefficient. The profile-drag coefficient at point B is not as low as at point A, unlike the polars of many laminar-flow airfoils where the drag coefficient within the laminar bucket is nearly constant. This characteristic is related to the elimination of significant (drag-producing) laminar separation bubbles on the upper surface. (See ref. 22.) The small increase in profile-drag coefficient with increasing lift coefficient is relatively inconsequential because the ratio of the profile drag to the total drag of the wind-turbine blade decreases with increasing lift coefficient. The profile-drag coefficient increases very rapidly outside the low-drag range because boundary-layer transition moves quickly toward the leading edge with increasing (or decreasing) lift coefficient. This feature results in a leading edge that produces a suction peak at higher lift coefficients, which ensures that transition on the upper surface will occur very near the leading edge. Thus, the maximum lift coefficient, point C, occurs with turbulent flow along the entire upper surface and, therefore, should be relatively insensitive to roughness at the leading edge.

Because the large airfoil thickness allows a wider low-drag range to be achieved than specified, the lower limit of the low-drag range should be below point A.

From the preceding discussion, the pressure distributions along the polar can be deduced. The pressure distribution at point A should look something like sketch 2.



Sketch 2

To achieve low drag, a favorable pressure gradient is desirable along the upper surface to about 60-percent chord. Aft of this point, a short region having a shallow, adverse pressure gradient ("transition ramp") promotes the efficient transition from laminar to turbulent flow (ref. 23). The transition ramp is followed by a nearly linear pressure recovery. The specific pressure recovery employed represents a compromise between maximum lift, drag, pitching moment, and stall characteristics. The steep, adverse pressure gradient aft of about 90-percent chord is a "separation ramp," originally proposed by F. X. Wortmann,[1] which confines turbulent separation to a small region near the trailing edge. By constraining the movement of the separation point at high angles of attack, high lift coefficients can be achieved with little drag penalty. This feature has the added benefit of promoting docile stall characteristics. (See ref. 24.)

A generally favorable pressure gradient is desirable along the lower surface to about 45-percent chord to achieve low drag. The specific pressure gradients employed along the forward portion of the lower surface increase the loading in the leading-edge region while maintaining low drag at the lower lift coefficients. The forward loading serves to balance, with respect to the pitching-moment constraint, the aft loading, both of which contribute to the achievement of the specified maximum lift coefficient and low profile-drag coefficients. This region is followed by a transition ramp and then a concave pressure recovery, which exhibits lower drag and has less tendency to separate than the corresponding linear or convex pressure recovery (ref. 23). The pressure recovery must begin relatively far forward to alleviate separation at lower lift coefficients, especially with transition fixed near the leading edge.

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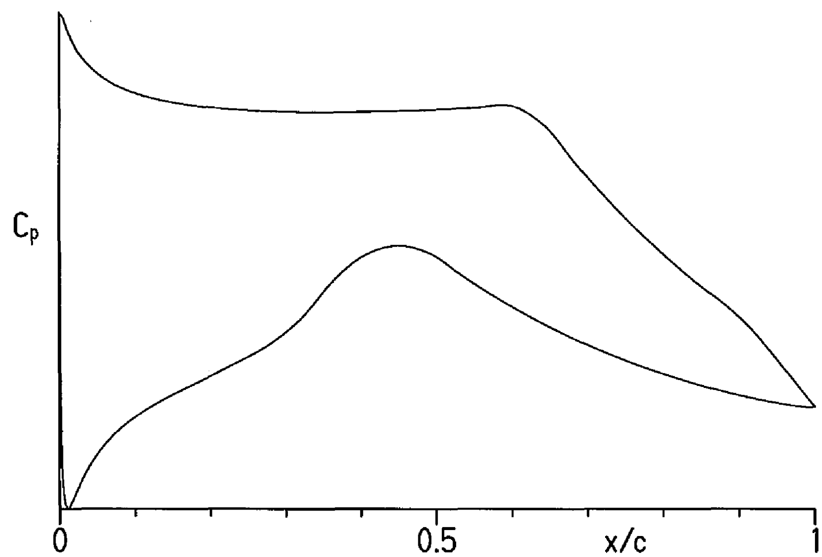
[1]Director, Institute for Aerodynamics and Gas Dynamics, University of Stuttgart, Germany.

The amounts of pressure recovery on the upper and lower surfaces are determined by the airfoil-thickness and pitching-moment constraints.

At point B, the pressure distribution should look like sketch 3.



Sketch 3

No suction spike exists at the leading edge. Instead, a rounded peak occurs just aft of the leading edge. Transition is essentially imminent over the entire forward portion of the upper surface. This feature allows a wider low-drag range to be achieved and higher lift coefficients to be reached without significant separation. It also causes transition to move very quickly toward the leading edge with increasing lift coefficient, which leads to the roughness insensitivity of the maximum lift coefficient.

EXECUTION

Given the pressure distributions previously discussed, the design of the airfoil is reduced to the inverse problem of transforming the pressure distributions into an airfoil shape. The Eppler Airfoil Design and Analysis Code (refs. 19 and 20) was used because of its unique capability for multipoint design and because of confidence gained during the design, analysis, and experimental verification of many other airfoils. (See refs. 25–28, for example.)

The airfoil is designated the S827. The airfoil shape is shown in figure 1 and the coordinates are contained in table II. The airfoil thickness is 21-percent chord, which satisfies the design constraint.

EXPERIMENTAL PROCEDURE

WIND TUNNEL

The NASA Langley Low-Turbulence Pressure Tunnel (LTPT) (refs. 17 and 18) is a closed-throat, single-return tunnel (fig. 2) that can be operated at stagnation pressures from 100 to 1000 kPa (1 to 10 atm). The unit Reynolds number can be varied from 1×10^6 to 49×10^6 per meter (0.3×10^6 to 15×10^6 per foot); the Mach number can be varied from 0.05 to 0.47. The turbulence level in the test section is generally below 0.05 percent for unit Reynolds numbers up to 13×10^6 per meter (4×10^6 per foot) at Mach numbers up to 0.15 (ref. 29).

The test section is 91.44 cm (36.00 in.) wide by 228.6 cm (90.00 in.) high. Hydraulically actuated circular plates provide positioning and attachment for the two-dimensional model (fig. 3). The plates, about 86 cm (34 in.) in diameter, are flush with the tunnel sidewalls and rotate with the model. The axis of rotation coincided approximately with the midchord of the model, which was mounted horizontally between the plates. The gaps between the model and the plates were sealed.

MODEL

The aluminum, wind-tunnel model was fabricated by Advanced Technologies, Incorporated, Newport News, Virginia, using a numerically controlled milling machine. The model had a chord of 457.23 mm (18.001 in.) and a span of 91.14 cm (35.88 in.). Upper- and lower-surface orifices were located to one side of midspan at the staggered positions listed in table III. All the orifices were 0.51 mm (0.020 in.) in diameter with their axes perpendicular to the surface. The surface of the model had been polished to ensure an aerodynamically smooth finish. The measured model contour was within 0.1 mm (0.005 in.) of the prescribed shape.

WAKE-SURVEY PROBE

A total- and static-pressure, wake-survey probe (fig. 4) was mounted to a traverse mechanism attached to the tunnel strut (fig. 3). The probe was positioned spanwise at the tunnel centerline. The traverse mechanism incrementally positioned the probe vertically. The tip of the probe was located 1.84 chord downstream of the trailing edge of the model.

INSTRUMENTATION

Measurements of the pressures on the model and in the wake were made by an electronically scanned, pressure-transducer system. Basic tunnel pressures were measured with precision quartz manometers. Data were obtained and recorded by an electronic data-acquisition system.

METHODS

The pressures measured on the model were reduced to standard pressure coefficients and numerically integrated to obtain section normal- and chord-force coefficients and section pitching-moment coefficients about the quarter-chord point. Section profile-drag coefficients were computed from the wake total and static pressures by the method of reference 21.

Standard, low-speed, wind-tunnel boundary corrections (ref. 30) have been applied to the section characteristics. The wake-survey-probe total-pressure-tube displacement correction (ref. 21) has been taken into account.

At angles of attack beyond stall, the unsteadiness of the flow and the large height of the wake made wake surveys impractical. Accordingly, at these angles of attack, the uncorrected profile-drag coefficient was set to $(c_{d,last})_u + \Delta c_d\,(\alpha_u - (\alpha_{last})_u)$, where Δc_d was determined from data presented in reference 31. Typically, the value of $(c_{d,last})_u$ was about 0.1.

TESTS

The model was tested at Reynolds numbers based on airfoil chord of 1×10^6, 2×10^6, 3×10^6, 4×10^6, and 6×10^6 and a Mach number of 0.1 with transition free (smooth) and with transition fixed by roughness at 2-percent chord on the upper surface and 5-percent chord on the lower surface. The grit roughness was sized using the method of reference 32 and sparsely distributed along 3-mm (0.1-in.) wide strips applied to the model with lacquer. (See table IV.) The model was also tested with a grit roughness equivalent to NACA standard roughness (ref. 4), which was applied to the model with lacquer and sparsely distributed from the leading edge to an arc length of 8-percent chord on the upper and lower surfaces. The grit size, nominally 0.211 mm (0.0083 in.), was scaled from the NACA standard-roughness grit size by the ratio of the model chords used: 457.2 mm (18.00 in.) in the present investigation and 609.6 mm (24.00 in.) in the NACA tests.

Starting from 0°, the angle of attack was increased and then decreased to determine hysteresis. The angle of attack was then decreased from 0° until the lift coefficient became negative.

DISCUSSION OF RESULTS

EXPERIMENTAL RESULTS

Pressure Distributions

The pressure distributions at various angles of attack for the design Reynolds number of 4×10^6 with transition free are shown in figure 5. At an angle of attack of 0.00° (fig. 5(a)), a short laminar separation bubble is evident on the upper surface around 70-percent chord and on the lower surface around 50-percent chord. As the angle of attack is increased, the bubble on the upper surface moves slightly forward, whereas the bubble on the lower surface moves slightly aft. At an angle of attack of 4.03° (fig. 5(e)), which corresponds approximately to the upper limit of the low-drag, lift-coefficient range, the bubble on the upper surface has almost disappeared. As the angle of attack is increased further, transition moves rapidly forward and turbulent, trailing-edge separation occurs on the upper surface. The separation point moves forward with increasing angle of attack until it reaches about 70-percent chord. The maximum lift coefficient occurs at an angle of attack of 16.07° (fig. 5(q)). As the angle of attack is increased further, the leading-edge pressure peak gradually collapses. At an angle of attack of 20.04° (fig. 5(u)), the flow around the leading edge is still attached.

As the angle of attack is decreased from 20.04°, the pressure distributions (figs. 5(v)–5(y)) are essentially identical to the ones that occur with increasing angle of attack (figs. 5(q)–5(t)). Thus, no hysteresis occurs with respect to separation on the upper surface.

As the angle of attack is decreased from −1.00° (fig. 5(z)), the laminar separation bubble on the lower surface moves slightly forward, whereas the bubble on the upper surface moves slightly aft. At an angle of attack of −2.01° (fig. 5(aa)), which corresponds approximately to the lower limit of the low-drag range, the bubble on the lower surface has almost disappeared.

Section Characteristics

Reynolds number effects.- The section characteristics with transition free, transition fixed, and the scaled, NACA standard roughness ("rough") are shown in figure 6. For the design Reynolds number of 4×10^6 with transition free (fig. 6(d)), the maximum lift coefficient is 1.28, which substantially exceeds the design objective of $c_{l,max} = 1.00$. The airfoil exhibits relatively docile stall characteristics, which meets the design goal. No hysteresis occurs for angles of attack beyond stall. Low profile-drag coefficients are exhibited over the range of lift coefficients from 0.04 to 0.75. Thus, the lower limit of the low-drag, lift-coefficient range is below the design objective of $c_{l,ll} = 0.20$, although the upper limit of the low-drag range is also below the design objective of $c_{l,ul} = 0.80$, primarily to meet other, more important goals. The drag coefficient at the specified lower limit of the low-drag range ($c_l = 0.20$) is 0.0049, which satisfies the design objective of $c_{d,min} \leq 0.0080$. The zero-lift pitching-moment coefficient is −0.07, which satisfies the design constraint of $c_{m,0} \geq -0.07$.

The effects of Reynolds number on the section characteristics with transition free, transition fixed, and rough are summarized in figure 7. The zero-lift angle of attack, approximately −2.9° with transition free, is relatively unaffected by Reynolds number. In general, the lift-curve slope, the maximum lift coefficient, the lower limit of the low-drag range, and the magnitude of the pitching-moment coefficients increase with increasing Reynolds number; the docility of the stall, the upper limit and the width of the low-drag range, and the drag coefficients decrease.

Effect of roughness.- The effect of fixing transition on the section characteristics is shown in figure 6. In general, the lift-curve slope, the maximum lift coefficient, and the magnitudes of the zero-lift angle of attack and the pitching-moment coefficients decrease with transition fixed. These results are primarily a consequence of the boundary-layer displacement effect, which decambers the airfoil because the displacement thickness is greater with transition fixed than with transition free. In addition, the lift-curve slope and the maximum lift coefficient decrease with transition fixed because the roughness induces earlier trailing-edge separation, particularly at higher angles of attack. The maximum lift coefficient for the design Reynolds number of 4×10^6 (fig. 6(d)) is 1.26, a reduction of less than 2 percent from that with transition free. Thus, one of the most important design goals has been achieved. The drag coefficients are, of course, adversely affected by the roughness. For many conditions, the Reynolds number, based on local velocity and boundary-layer momentum thickness, at the roughness location is too low to support turbulent flow. Accordingly, to force transition, the roughness must be so large that it increases the momentum thickness, which abnormally decreases the lift coefficients and the magnitude of the pitching-moment coefficients and increases the drag coefficients. Conversely, at low lift coefficients, the roughness on the upper surface, which was sized for higher lift coefficients, was occasionally too small to force transition, resulting in improperly low drag coefficients.

The effect of the scaled, NACA standard roughness on the section characteristics is shown in figure 6. The effect is more severe than that of fixing transition. The maximum lift coefficient for the design Reynolds number of 4×10^6 (fig. 6(d)) is 1.06, a reduction of 17 percent from that with transition free. It should be remembered that the effect of roughness is proportional to the ratio of the roughness height to the boundary-layer thickness. Because the height of the scaled, NACA standard roughness and the airfoil chord are constant, the effect of this roughness generally increases with increasing Reynolds number (because increasing Reynolds number results in decreasing boundary-layer thickness).

The variation of maximum lift coefficient with Reynolds number is shown in figure 8. The maximum lift coefficient increases with increasing Reynolds number. The rate of increase is similar with transition free and transition fixed but much lower with the scaled, NACA standard roughness.

The variation of the change in maximum lift coefficient due to roughness with Reynolds number is shown in figure 9. The magnitude of the change due to fixing transition is relatively small (< 4 percent) and exhibits no definite trend with Reynolds number. The magnitude of the change due to the scaled, NACA standard roughness is an order of magnitude larger and increases with increasing Reynolds number.

The variation of profile-drag coefficient at a lift coefficient of about 0.2 (i.e., approximately the specified lower limit of the low-drag range) with Reynolds number is shown in figure 10. The drag coefficient generally decreases with increasing Reynolds number. (The drag coefficient for a Reynolds number of 1×10^6 with transition fixed is too low probably because the roughness on the upper surface failed to force transition at this lift coefficient.)

COMPARISON OF THEORETICAL AND EXPERIMENTAL RESULTS

Pressure Distributions

The comparison of the theoretical and experimental pressure distributions at various lift coefficients is shown in figure 11. The theoretical pressure distributions are inviscid and incompressible; the experimental pressure distributions were obtained for a Reynolds number of 4×10^6 and a Mach number of 0.1 with transition free. It should be noted that the theoretical lift coefficient is calculated from the lift-curve slope and the angle of attack relative to the zero-lift line, whereas the experimental lift coefficient is derived from the integrated pressure distribution. (See refs. 19–21.) Thus, the theoretical and experimental pressure distributions at a given lift coefficient do not necessarily have identical areas.

Although the pressure coefficients at the lift coefficient that corresponds approximately to the specified lower limit of the low-drag range (fig. 11(a)) do not match exactly, the pressure gradients agree well except where laminar separation bubbles are present and near the trailing edge. The bubbles are not modeled in the pressure distributions predicted by the method of references 19 and 20. At the lift coefficient that corresponds approximately to the specified upper limit of the low-drag range (fig. 11(b)) and at the lift coefficient that corresponds approximately to the specified maximum lift coefficient (fig. 11(c)), the agreement is poor primarily because the effect of the upper-surface, trailing-edge separation on the pressure distribution is not modeled in the theory.

Section Characteristics

The comparison of the theoretical and experimental section characteristics with transition free is shown in figure 12. The magnitude of the zero-lift angle of attack is overpredicted. The lift-curve slope is generally predicted accurately. The maximum lift coefficient is significantly underpredicted (~20%) and increasingly underpredicted with increasing Reynolds number. It should be noted that the maximum lift coefficient computed by the method of references 19 and 20 is not always realistic. Accordingly, an empirical criterion has been applied to the computed results. This criterion assumes that the maximum lift coefficient has been reached if the drag coefficient of the upper surface is greater than $0.0160\ (2 \times 10^6/R)^{1/7}$ or if the length of turbulent separation on the upper surface is greater than 0.1000c. The lower limit of the low-drag range is generally underpredicted. The upper limit of the low-drag range and the drag coefficients within the low-drag range are generally predicted accurately. Thus, the width of the low-drag range is generally overpredicted. The magnitude of the pitching-moment coefficients is generally overpredicted.

The comparison of the theoretical and experimental section characteristics with transition fixed is shown in figure 13. The predicted zero-lift angle of attack, lift-curve slope, maximum lift coefficient, and pitching-moment coefficients show the same tendencies as with transition free. The agreement between the predicted and measured drag coefficients is poor at low lift coefficients for Reynolds numbers of 1×10^6 and 2×10^6, probably because the roughness on the upper surface failed to force transition at these lift coefficients.

CONCLUDING REMARKS

A 21-percent-thick, natural-laminar-flow airfoil, the S827, for the 75-percent blade radial station of 40- to 50-meter, stall-regulated, horizontal-axis wind turbines has been designed and analyzed theoretically and verified experimentally in the NASA Langley Low-Turbulence Pressure Tunnel. The primary objective of restrained maximum lift coefficient has not been achieved, although the maximum lift coefficient is relatively insensitive to leading-edge roughness, which meets the design goal. The airfoil exhibits relatively docile stall characteristics, which meets the design goal. The primary objective of low profile-drag coefficients has been achieved. The constraints on the zero-lift pitching-moment coefficient and the airfoil thickness have been satisfied. Comparisons of the theoretical and experimental results generally show good agreement with the exception of maximum lift coefficient, which is significantly underpredicted.

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TABLE I.– AIRFOIL DESIGN SPECIFICATIONS

Parameter	Objective/Constraint
Blade radial station	0.75
Reynolds number R	4×10^6
Maximum lift coefficient $c_{l,max}$	1.00
Lower limit of low-drag, lift-coefficient range $c_{l,ll}$	0.20
Upper limit of low-drag, lift-coefficient range $c_{l,ul}$	0.80
Minimum profile-drag coefficient $c_{d,min}$	≤ 0.0080
Zero-lift pitching-moment coefficient $c_{m,0}$	≥ -0.07
Airfoil thickness t/c	21%

TABLE II.– S827 AIRFOIL COORDINATES

Upper Surface		Lower Surface	
x/c	z/c	x/c	z/c
0.00003	0.00054	0.00010	–0.00098
.00040	.00228	.00075	–.00240
.00327	.00789	.00194	–.00390
.01168	.01688	.00388	–.00572
.02501	.02661	.01440	–.01227
.04304	.03671	.03068	–.01907
.06557	.04692	.05249	–.02597
.09234	.05703	.07952	–.03303
.12305	.06686	.11138	–.04031
.15735	.07623	.14752	–.04794
.19486	.08497	.18727	–.05596
.23516	.09293	.22978	–.06438
.27779	.09996	.27409	–.07310
.32229	.10593	.31892	–.08183
.36815	.11068	.36288	–.08933
.41487	.11409	.40597	–.09376
.46193	.11603	.44906	–.09443
.50881	.11636	.49274	–.09126
.55498	.11490	.53770	–.08456
.59988	.11131	.58417	–.07538
.64347	.10497	.63172	–.06463
.68639	.09591	.67984	–.05305
.72880	.08503	.72787	–.04136
.77025	.07315	.77506	–.03025
.81021	.06086	.82049	–.02035
.84805	.04872	.86316	–.01216
.88305	.03718	.90192	–.00603
.91460	.02643	.93560	–.00204
.94236	.01682	.96306	–.00001
.96586	.00900	.98337	.00052
.98413	.00360	.99581	.00025
.99591	.00078	1.00000	.00000
1.00000	.00000		

TABLE III.- MODEL ORIFICE LOCATIONS

[c = 457.23 mm (18.001 in.)]

Upper Surface		Lower Surface	
x/c	y, mm (in.)	x/c	y, mm (in.)
−0.00013	152.3 (5.996)	0.00159	217.4 (8.558)
.00232	153.2 (6.032)	.00330	216.2 (8.513)
.00443	154.2 (6.071)	.00588	215.2 (8.471)
.00631	155.3 (6.113)	.00829	214.0 (8.426)
.00824	156.2 (6.149)	.01186	213.0 (8.384)
.01224	157.3 (6.191)	.01604	211.9 (8.341)
.01650	158.3 (6.233)	.02009	210.9 (8.302)
.02038	159.4 (6.276)	.02606	209.9 (8.262)
.02660	160.5 (6.318)	.03213	209.0 (8.228)
.03246	161.4 (6.356)	.03988	207.9 (8.184)
.04064	162.4 (6.394)	.04999	206.9 (8.147)
.05066	163.4 (6.434)	.06200	205.9 (8.108)
.06257	164.5 (6.475)	.07749	204.4 (8.045)
.07813	166.0 (6.537)	.09927	202.6 (7.975)
.10066	167.9 (6.611)	.12396	200.6 (7.896)
.12506	170.0 (6.692)	.14956	198.4 (7.810)
.15016	171.9 (6.766)	.17445	196.7 (7.744)
.17544	173.9 (6.847)	.19959	194.4 (7.654)
.20012	176.0 (6.929)	.22467	192.2 (7.568)
.22526	178.0 (7.007)	.24937	190.5 (7.500)
.25027	180.0 (7.088)	.27474	188.4 (7.419)
.27485	181.9 (7.161)	.29987	186.4 (7.340)
.30019	184.1 (7.250)	.32434	184.4 (7.260)
.32547	186.2 (7.330)	.34954	182.4 (7.180)
.35055	188.2 (7.411)	.37482	180.1 (7.093)
.37514	190.3 (7.493)	.39982	177.9 (7.004)
.40040	192.2 (7.567)	.41025	177.1 (6.972)
.42545	194.4 (7.653)	.41972	176.1 (6.934)
.45031	196.3 (7.730)	.43017	175.0 (6.890)
.47539	198.4 (7.812)	.43920	173.9 (6.848)
.50021	200.5 (7.893)	.45020	173.1 (6.813)
.52531	202.6 (7.975)	.46016	172.1 (6.774)
.55014	204.5 (8.051)	.47037	170.9 (6.727)
.57536	206.6 (8.133)	.48054	170.0 (6.693)
.60013	208.7 (8.219)	.49093	169.0 (6.654)
.61038	209.7 (8.254)	.50041	168.0 (6.614)
.62053	210.5 (8.289)	.51074	167.3 (6.586)
.63030	211.7 (8.335)	.52086	166.0 (6.536)

TABLE III.- Concluded

[c = 457.23 mm (18.001 in.)]

Upper Surface		Lower Surface	
x/c	y, mm (in.)	x/c	y, mm (in.)
0.64026	212.7 (8.373)	0.53063	165.0 (6.495)
.65004	213.8 (8.417)	.54038	163.9 (6.452)
.66019	214.7 (8.454)	.55053	163.0 (6.416)
.67001	215.7 (8.491)	.56062	162.1 (6.382)
.68022	216.8 (8.537)	.57063	161.0 (6.339)
.69054	217.5 (8.562)	.58070	159.8 (6.292)
.70011	218.8 (8.614)	.59036	158.9 (6.258)
.71042	219.9 (8.659)	.60067	157.7 (6.210)
.72027	220.7 (8.690)	.62064	159.2 (6.268)
.72998	221.7 (8.726)	.65080	161.4 (6.355)
.74017	222.8 (8.772)	.70071	165.3 (6.508)
.74999	223.8 (8.813)	.75103	169.0 (6.654)
.77019	221.0 (8.699)	.80060	172.7 (6.800)
.80088	216.9 (8.537)	.85042	176.6 (6.951)
.85008	209.7 (8.257)	.87843	178.7 (7.037)
.88026	205.3 (8.081)	.90035	180.6 (7.112)
.90056	202.3 (7.965)	.92042	181.7 (7.152)
.92033	199.5 (7.854)	.94040	183.5 (7.224)
.94041	196.6 (7.740)	.96019	184.6 (7.269)
.96035	193.7 (7.628)	.98022	186.1 (7.326)
.98031	190.8 (7.511)	.99021	186.7 (7.352)
.99040	189.5 (7.459)	.99972	188.1 (7.406)

TABLE IV.- ROUGHNESS LOCATION AND SIZE

<table>
<tr><th rowspan="2">Reynolds Number</th><th colspan="3">Upper Surface</th><th colspan="3">Lower Surface</th></tr>
<tr><th>x/c</th><th>Grit Number</th><th>Nominal Size, mm (in.)</th><th>x/c</th><th>Grit Number</th><th>Nominal Size, mm (in.)</th></tr>
<tr><td>1×10^6</td><td rowspan="5">0.02</td><td>90</td><td>0.178 (0.0070)</td><td rowspan="5">0.05</td><td>54</td><td>0.351 (0.0138)</td></tr>
<tr><td>2×10^6</td><td>180</td><td>0.089 (0.0035)</td><td>80</td><td>0.211 (0.0083)</td></tr>
<tr><td>3×10^6</td><td rowspan="3">220</td><td rowspan="3">0.074 (0.0029)</td><td rowspan="2">100</td><td rowspan="2">0.150 (0.0059)</td></tr>
<tr><td>4×10^6</td></tr>
<tr><td>6×10^6</td><td>180</td><td>0.089 (0.0035)</td></tr>
</table>

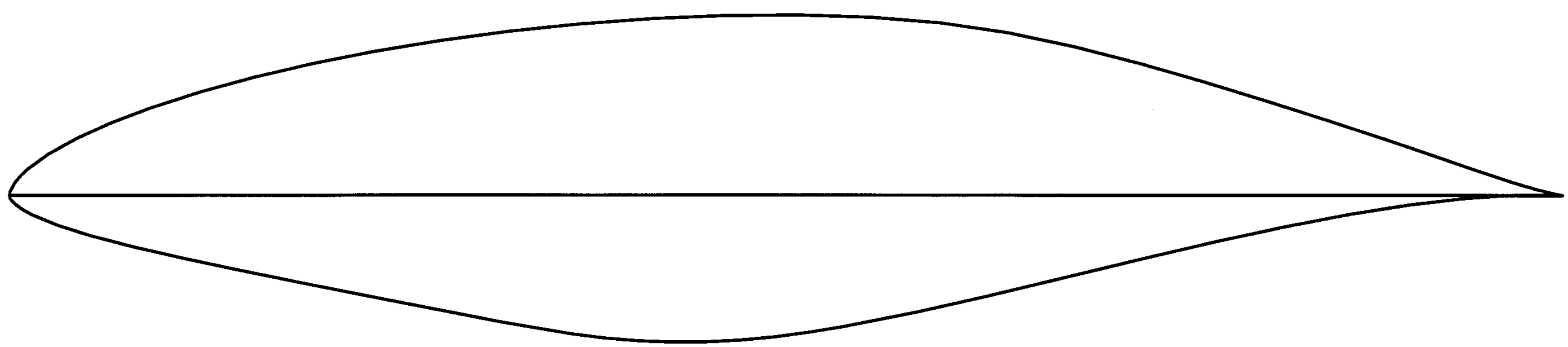


Figure 1.- S827 airfoil shape.

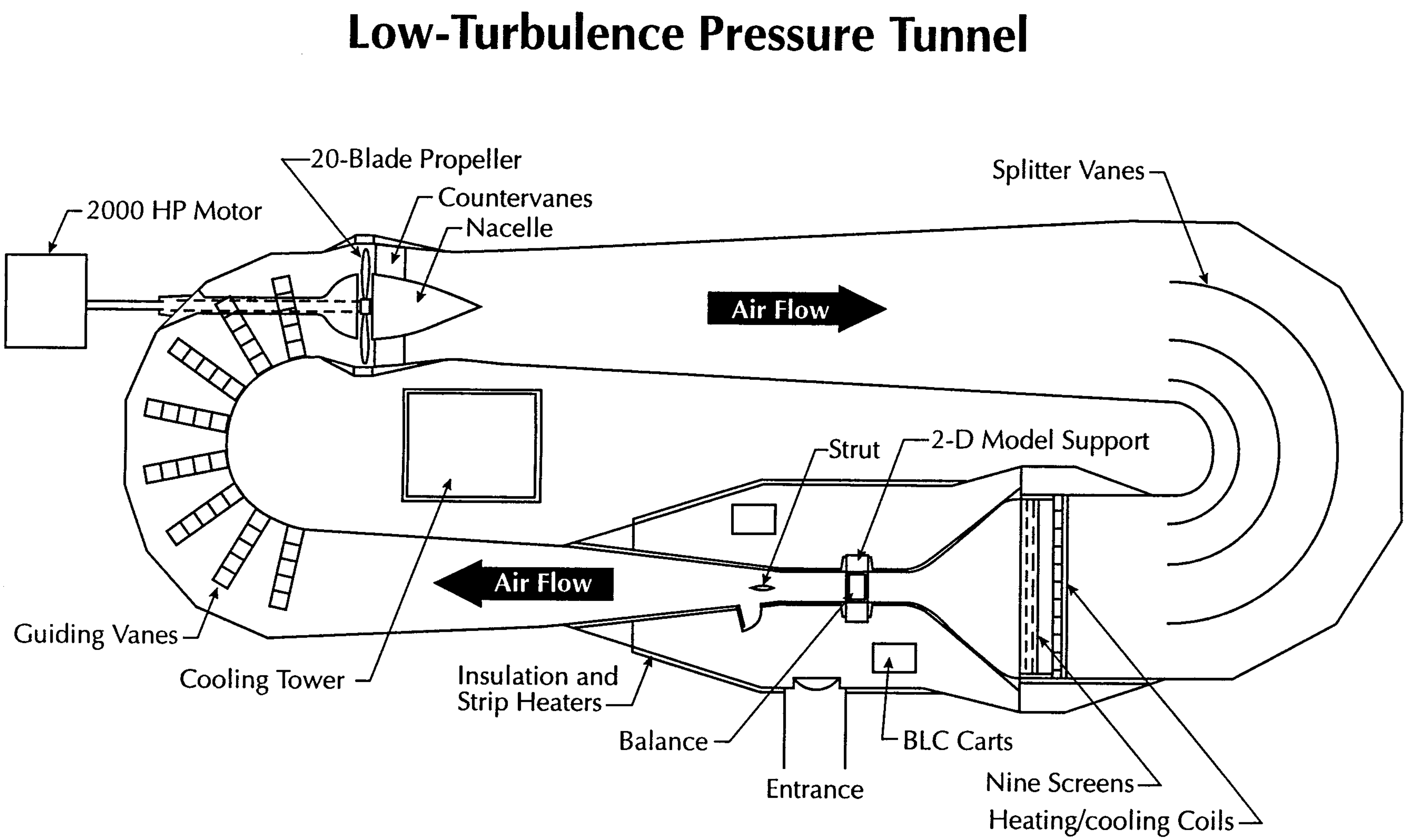


Figure 2.- NASA Langley Low-Turbulence Pressure Tunnel.

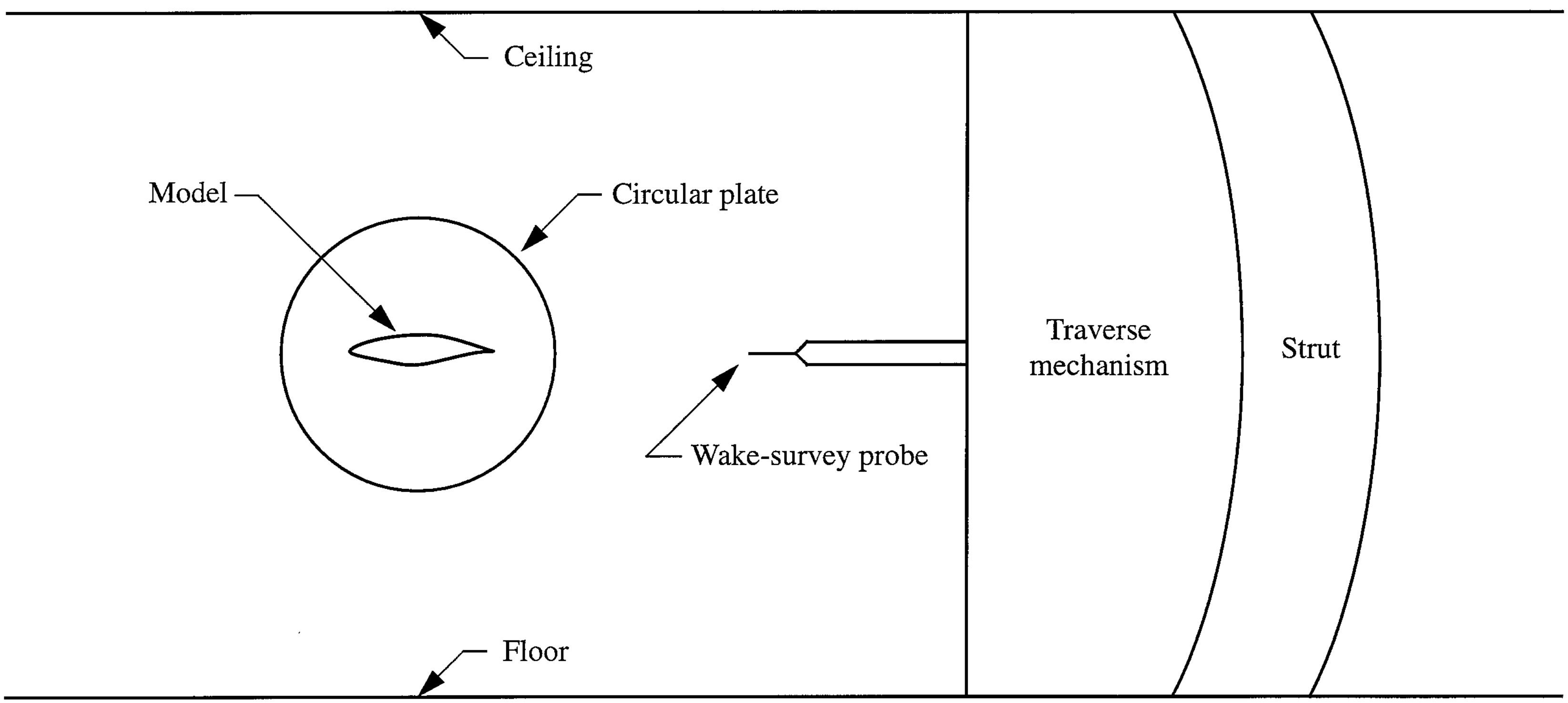


Figure 3.- Sketch of model and wake-survey probe mounted in test section.

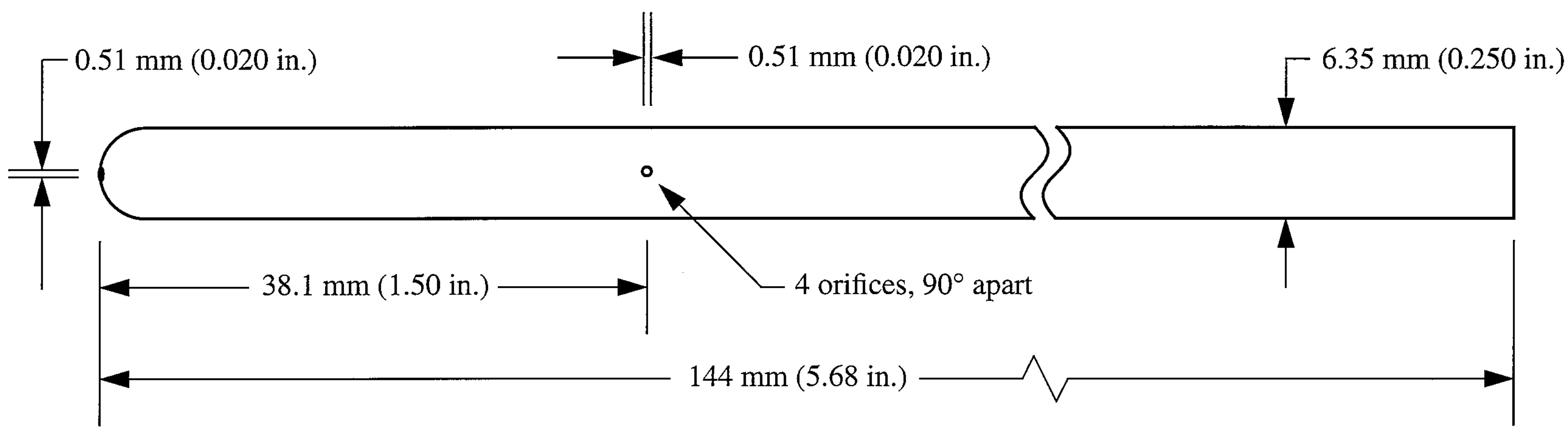
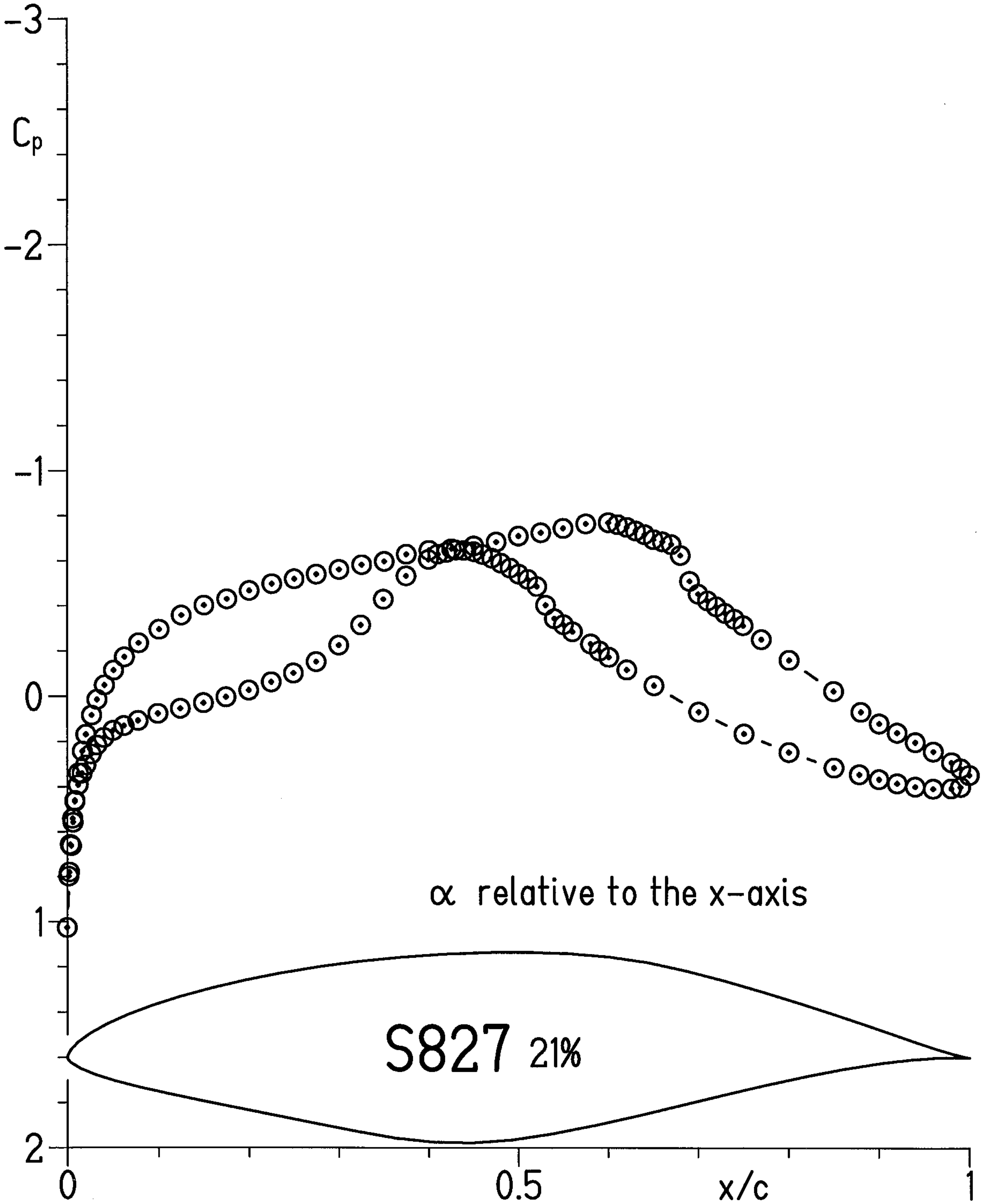
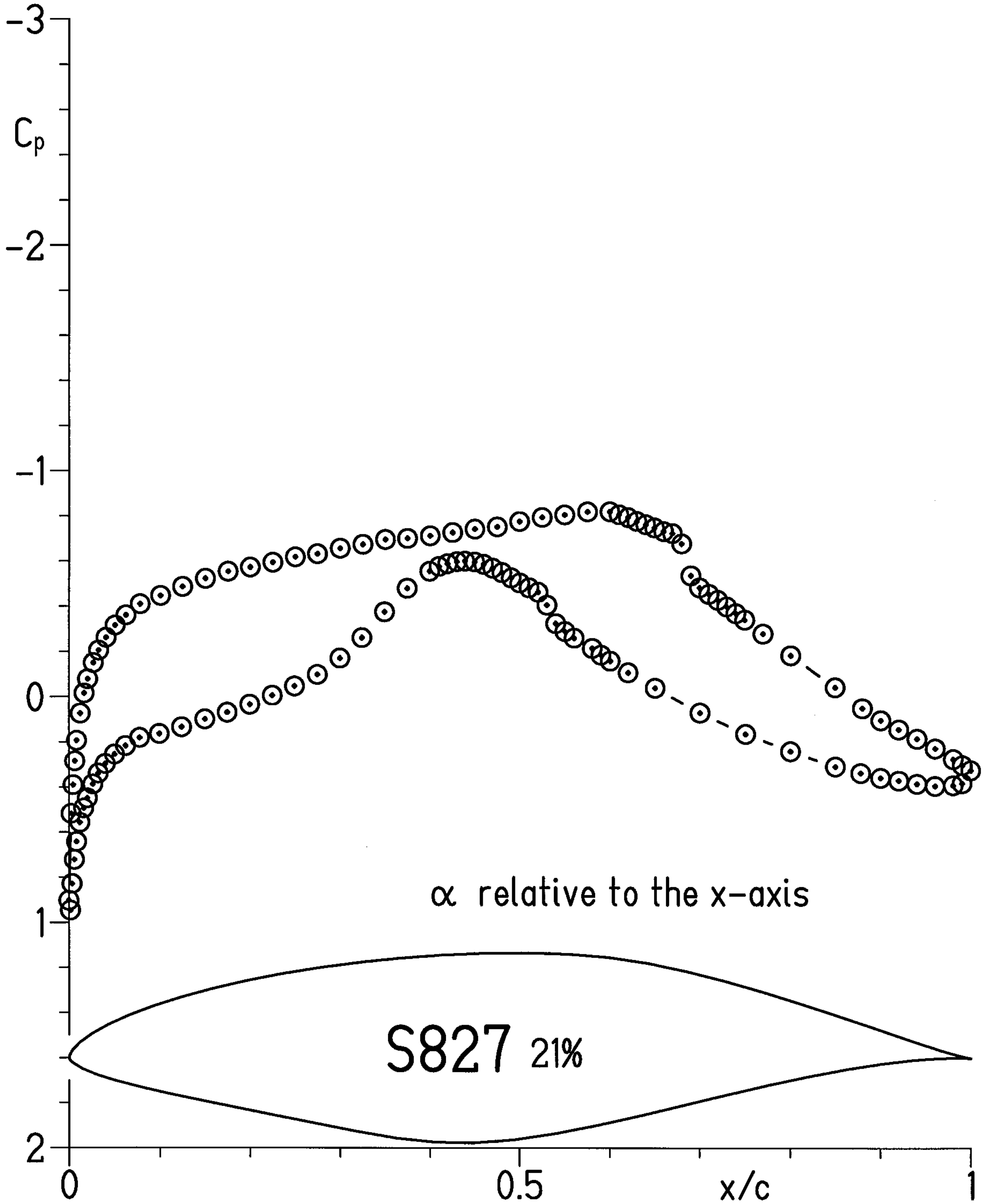


Figure 4.- Wake-survey probe.



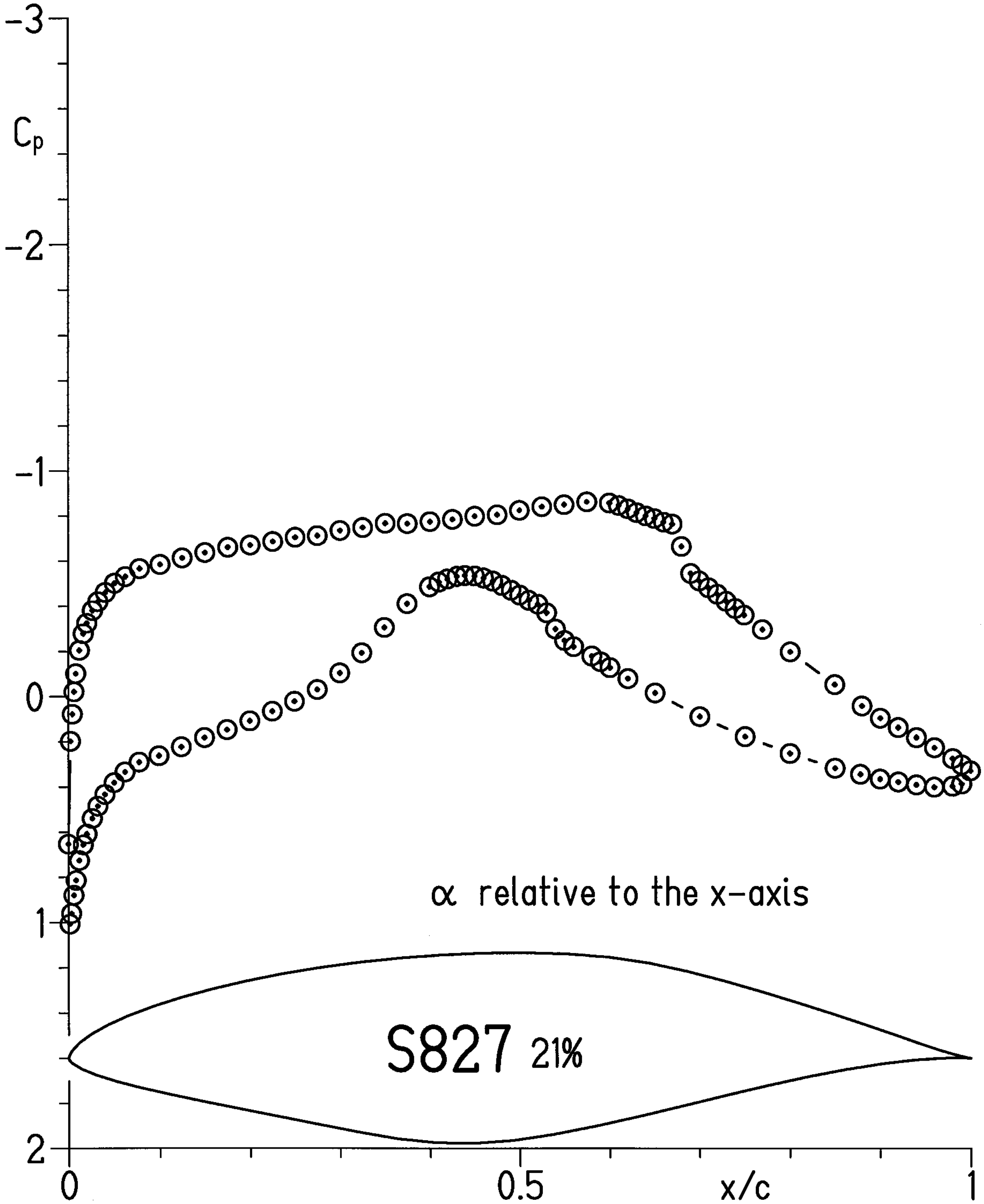
(a) $\alpha = 0.00°$.

Figure 5.- Pressure distributions for $R = 4 \times 10^6$ with transition free.



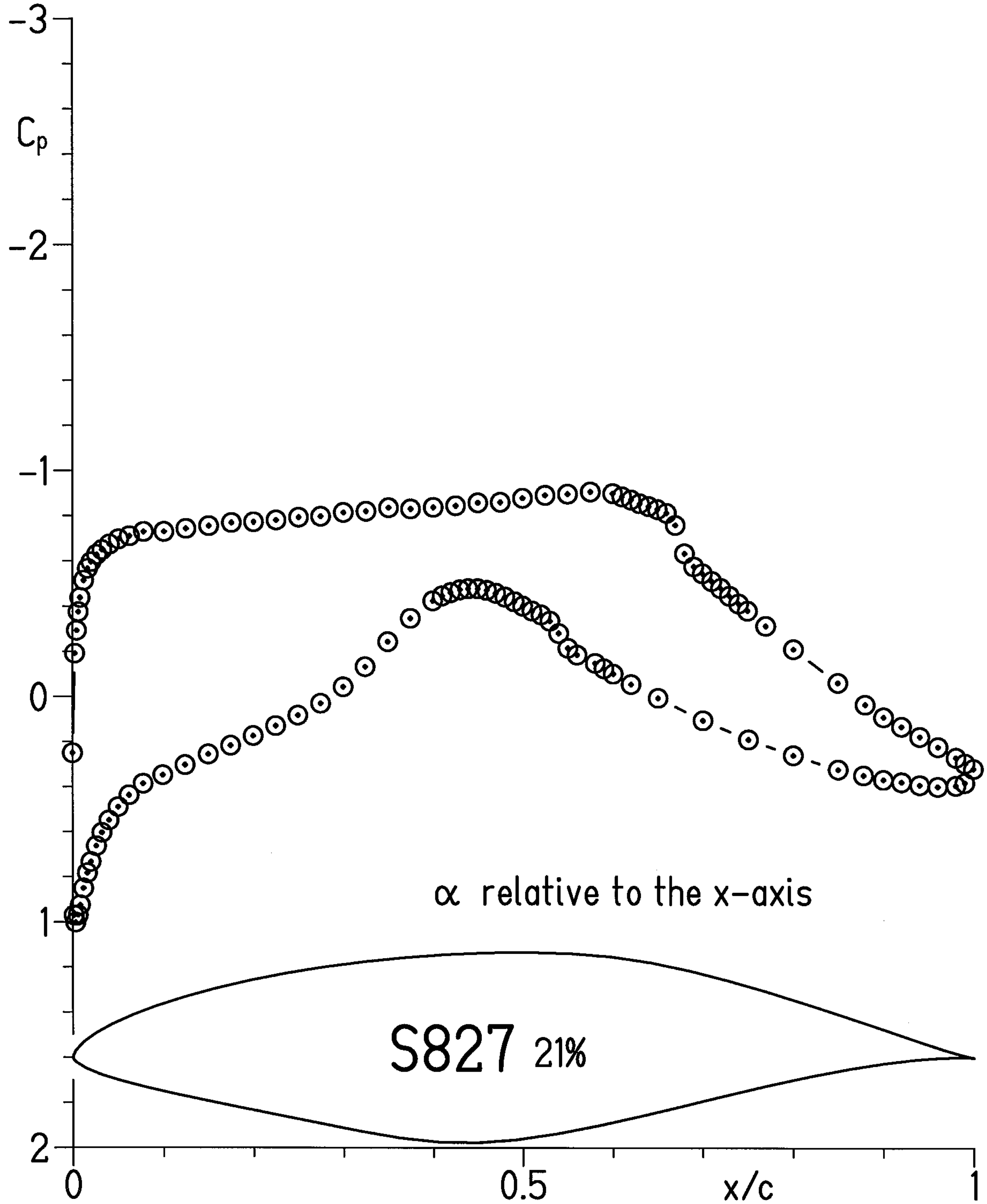
(b) $\alpha = 1.01°$.

Figure 5.- Continued.



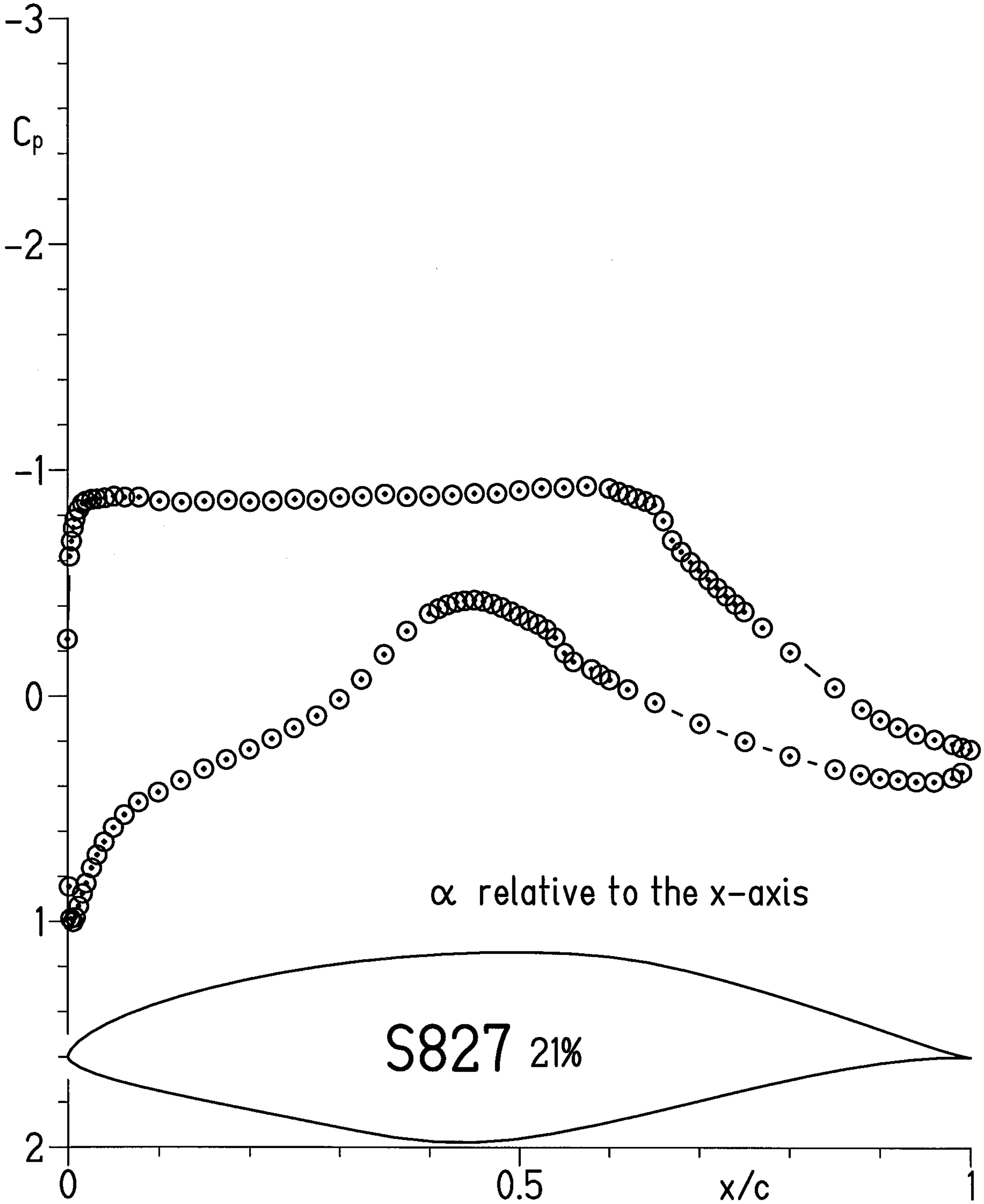
(c) $\alpha = 2.03°$.

Figure 5.- Continued.



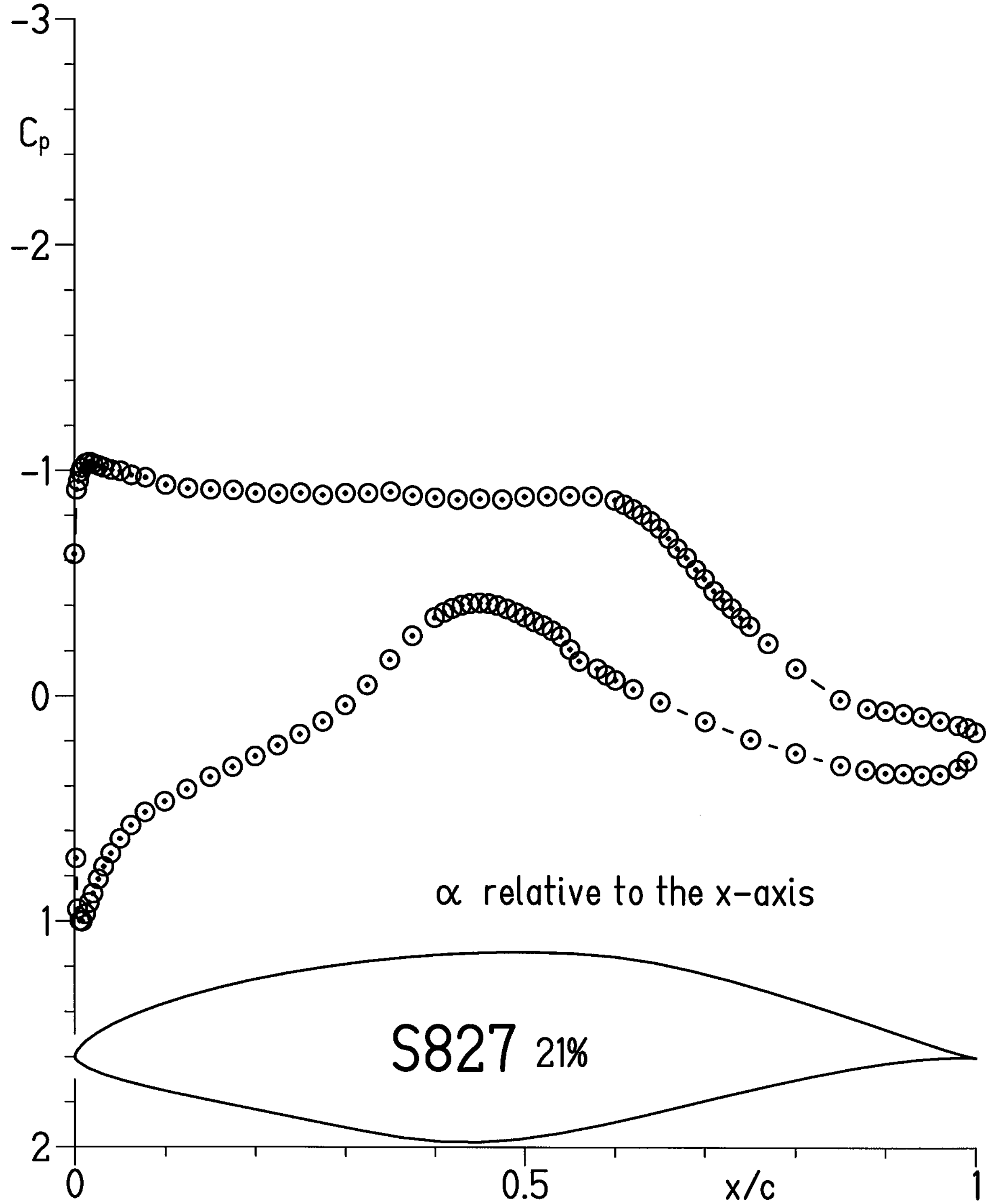
(d) α = 3.03°.

Figure 5.- Continued.



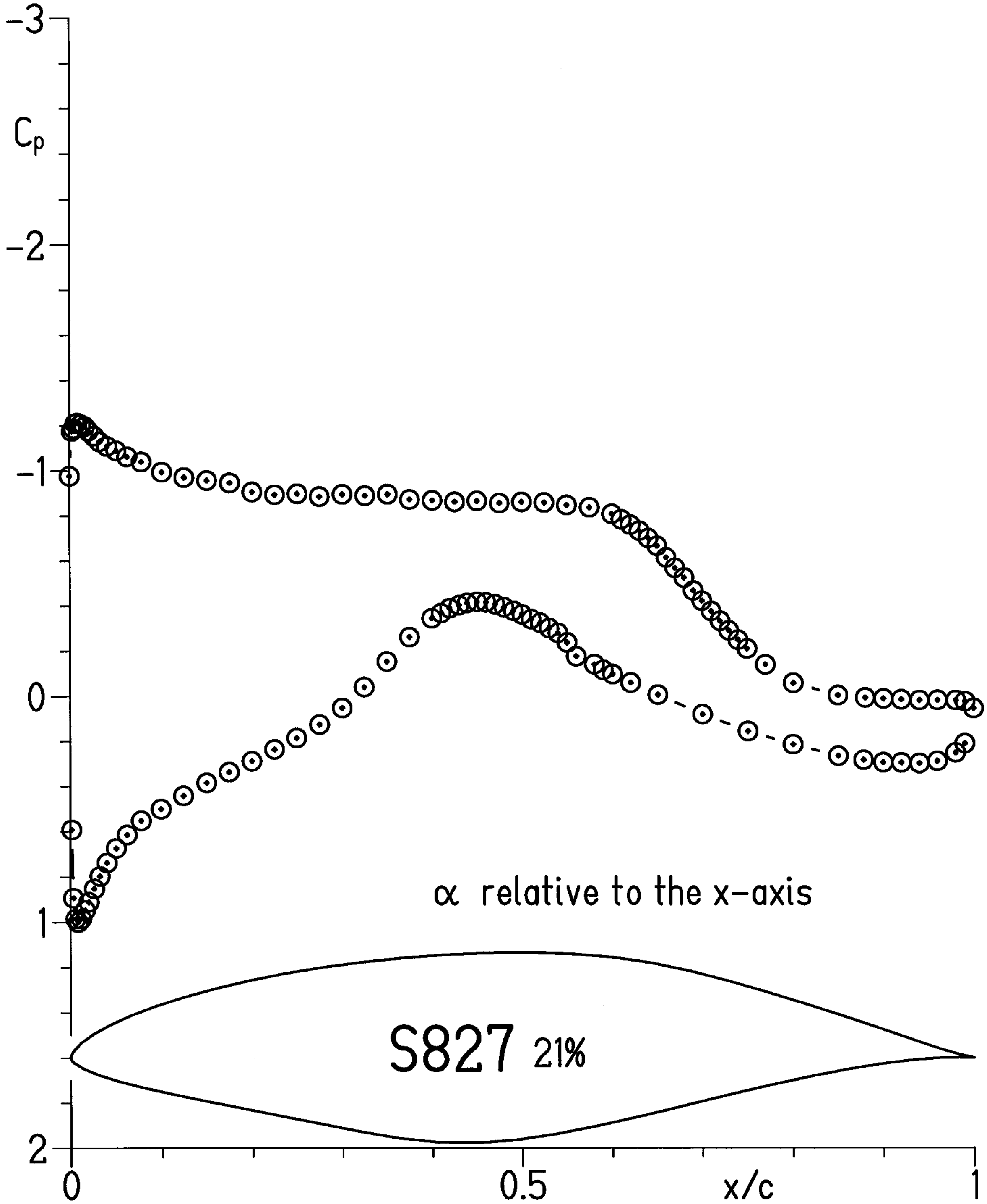
(e) $\alpha = 4.03°$.

Figure 5.- Continued.



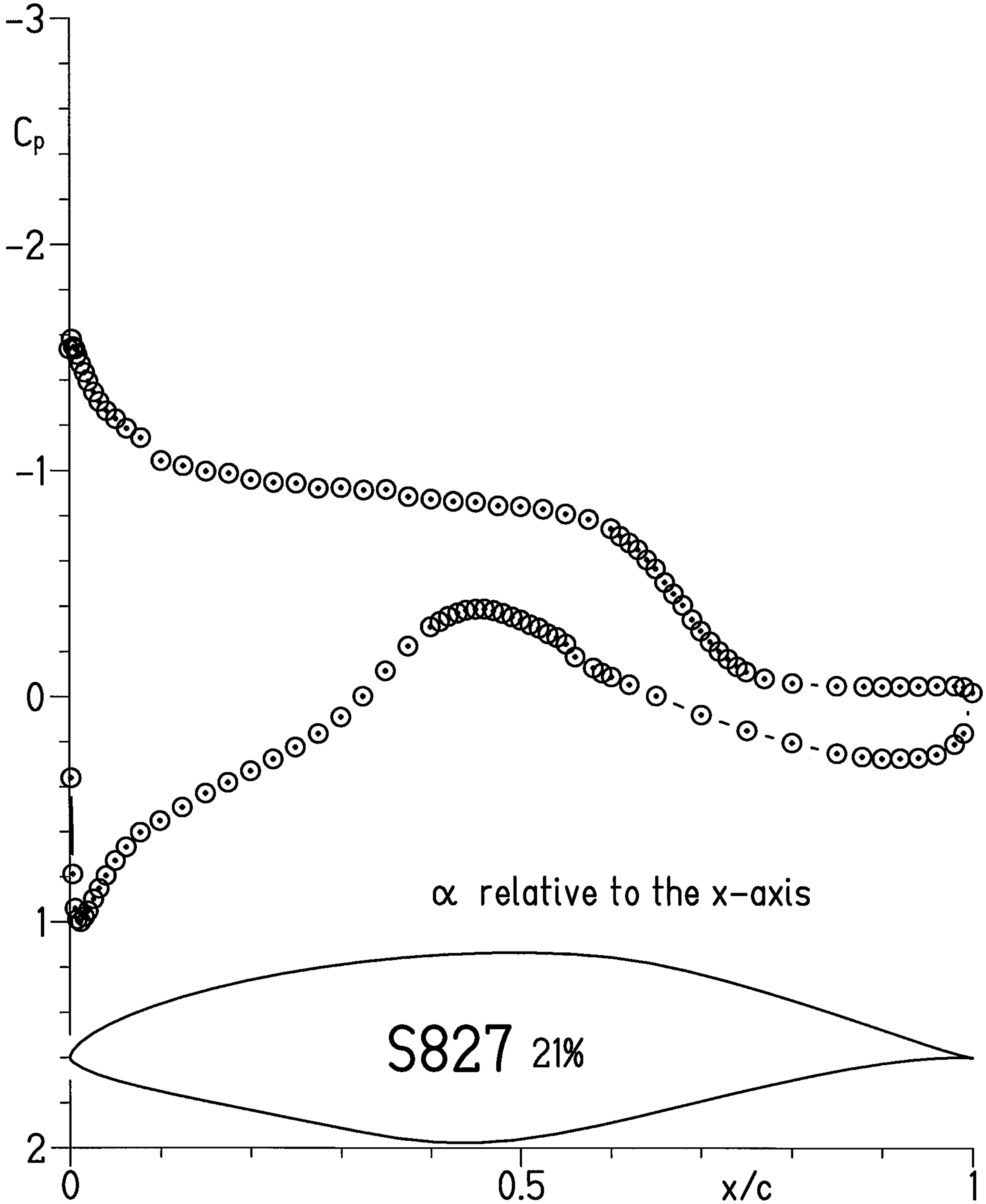
(f) $\alpha = 5.04°$.

Figure 5.- Continued.



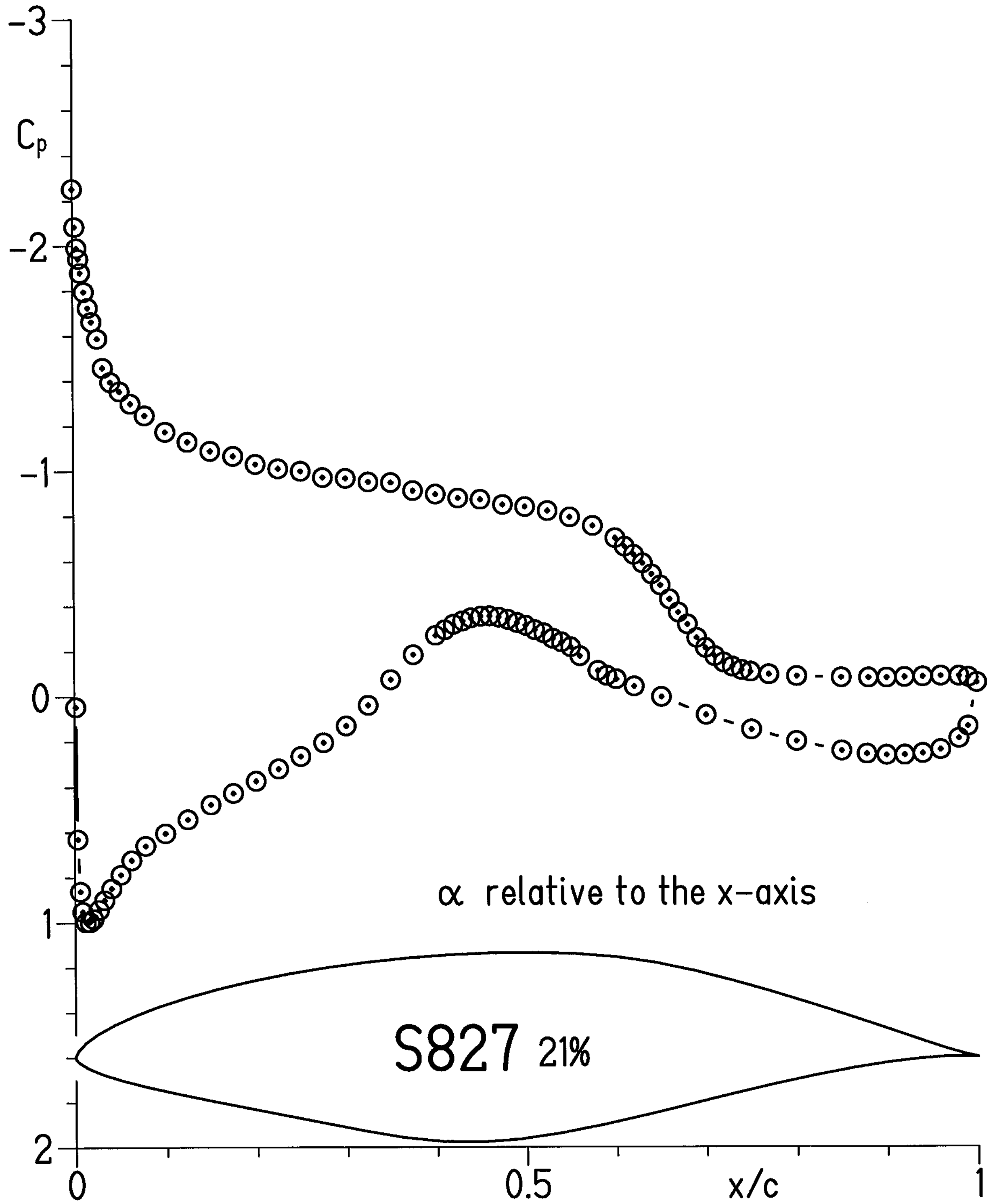
(g) $\alpha = 6.04°$.

Figure 5.- Continued.



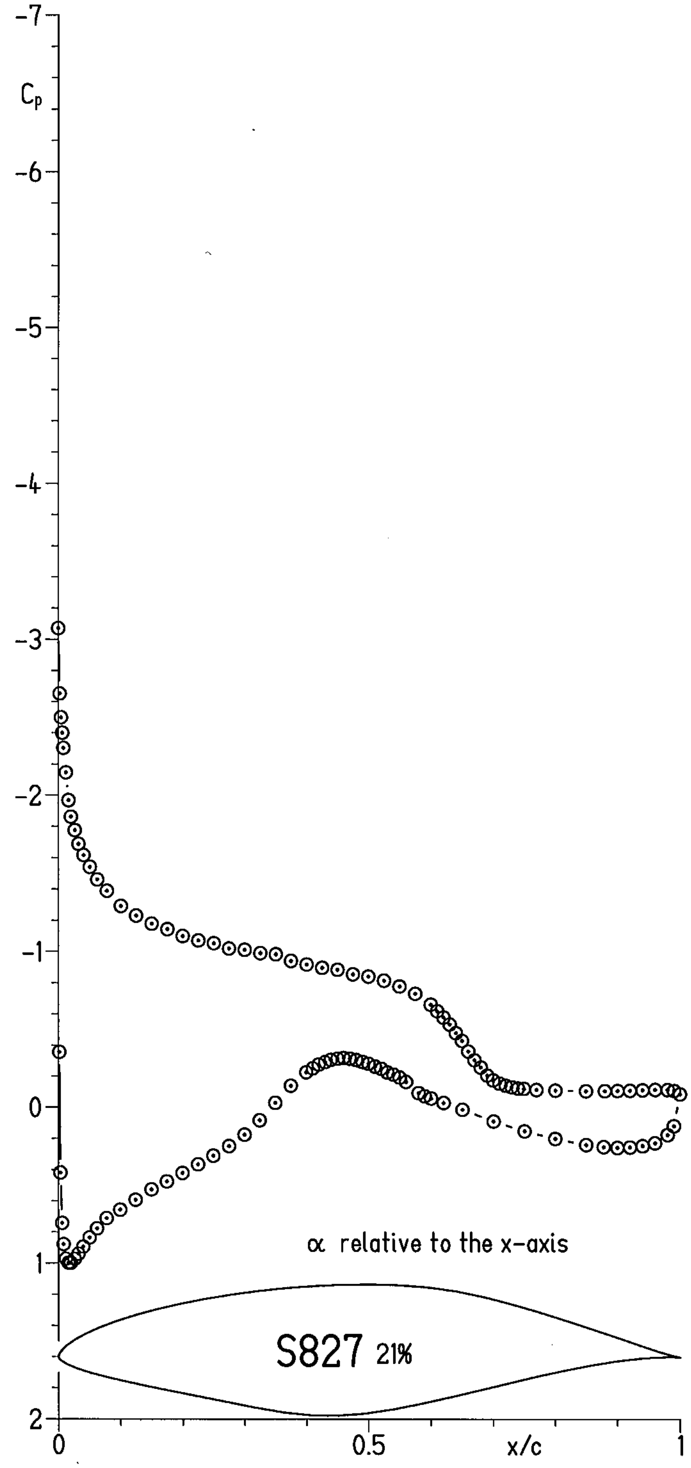
(h) $\alpha = 7.03°$.

Figure 5.- Continued.



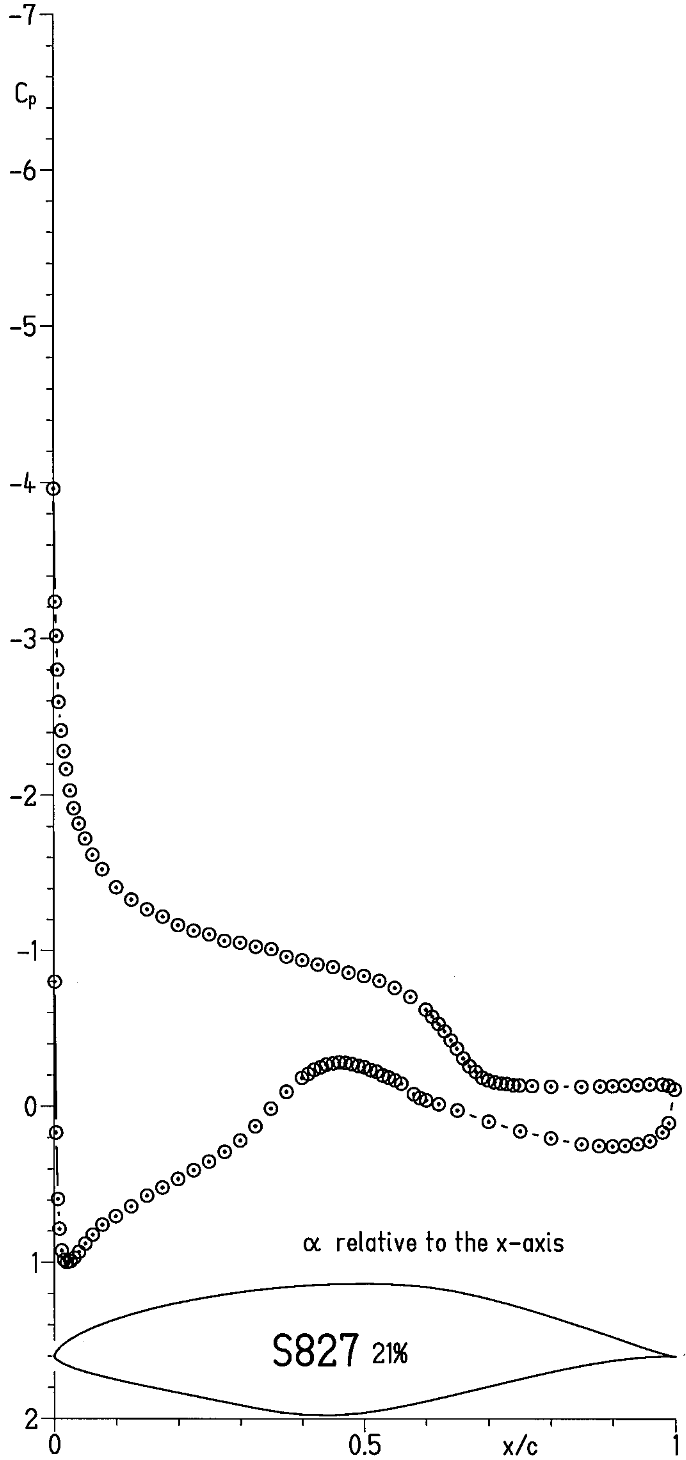
(i) $\alpha = 8.05°$.

Figure 5.- Continued.



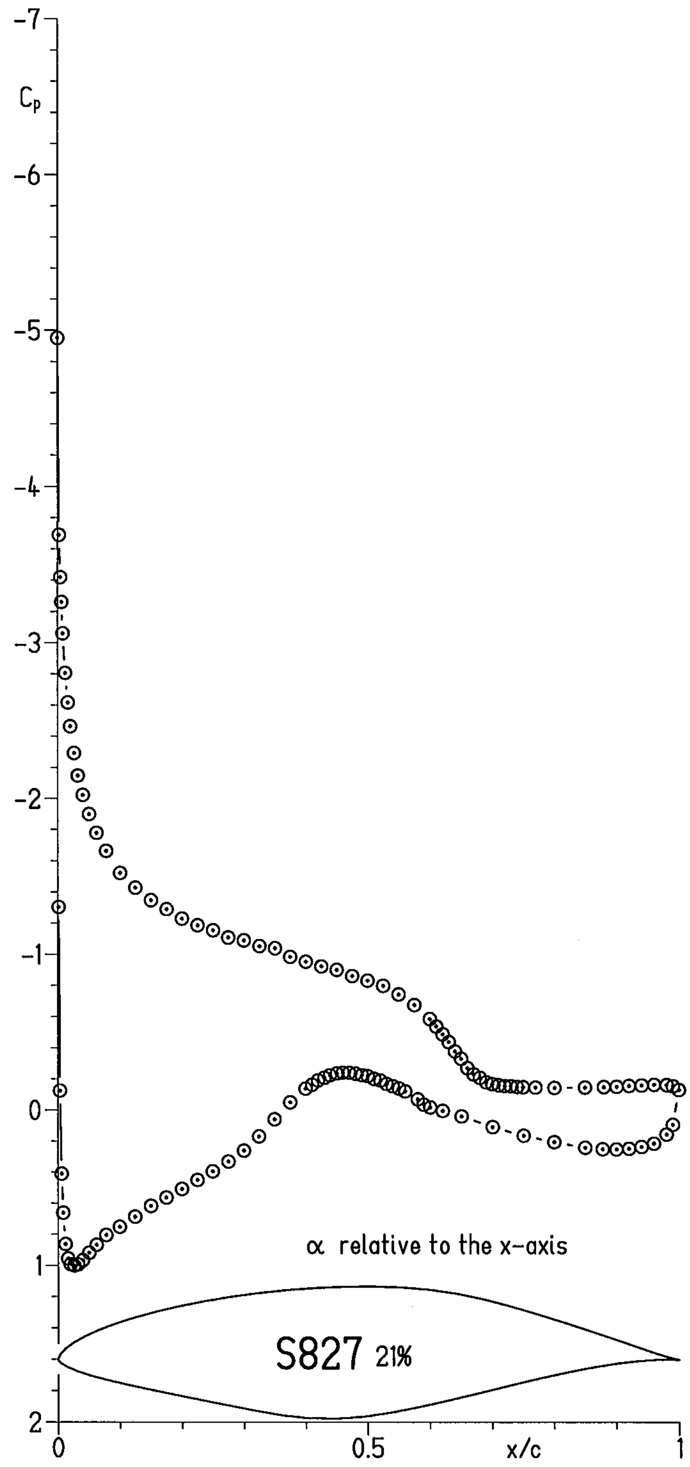
(j) $\alpha = 9.05°$.

Figure 5.- Continued.



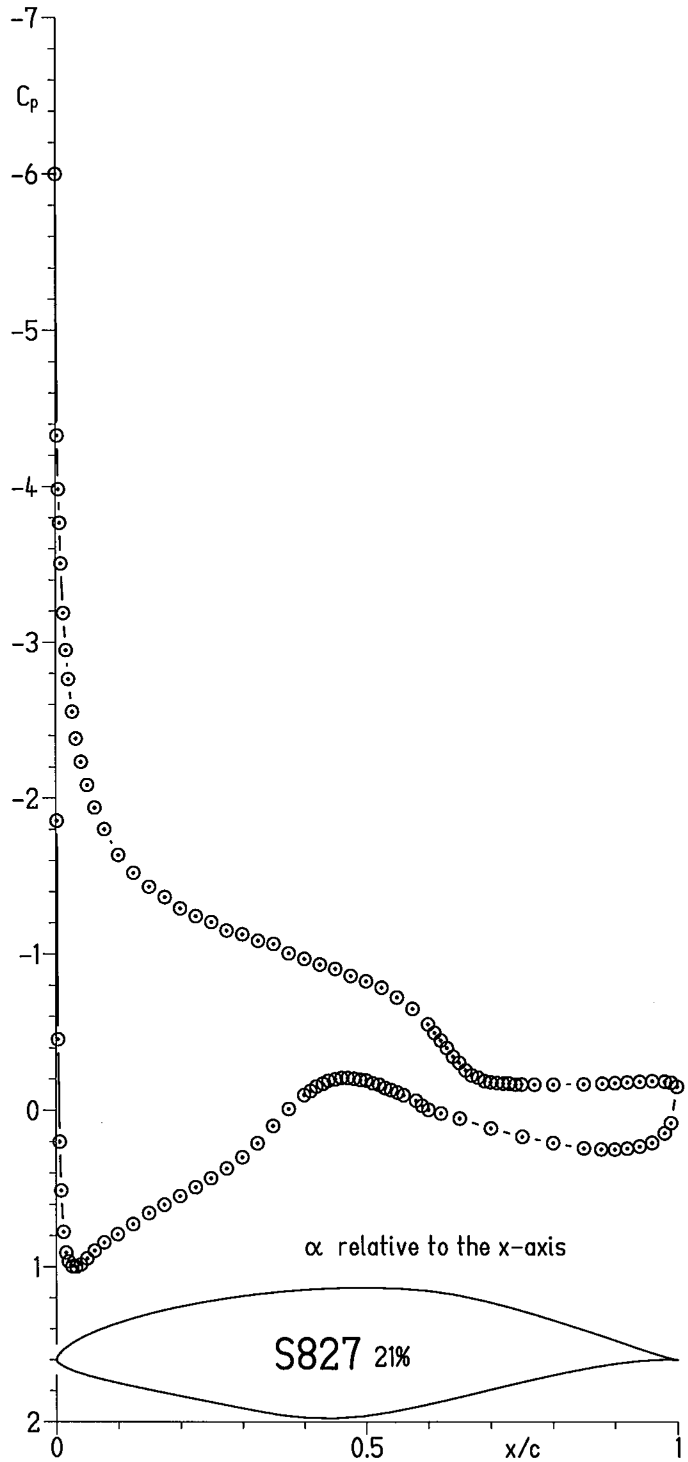
(k) $\alpha = 10.05°$.

Figure 5.- Continued.



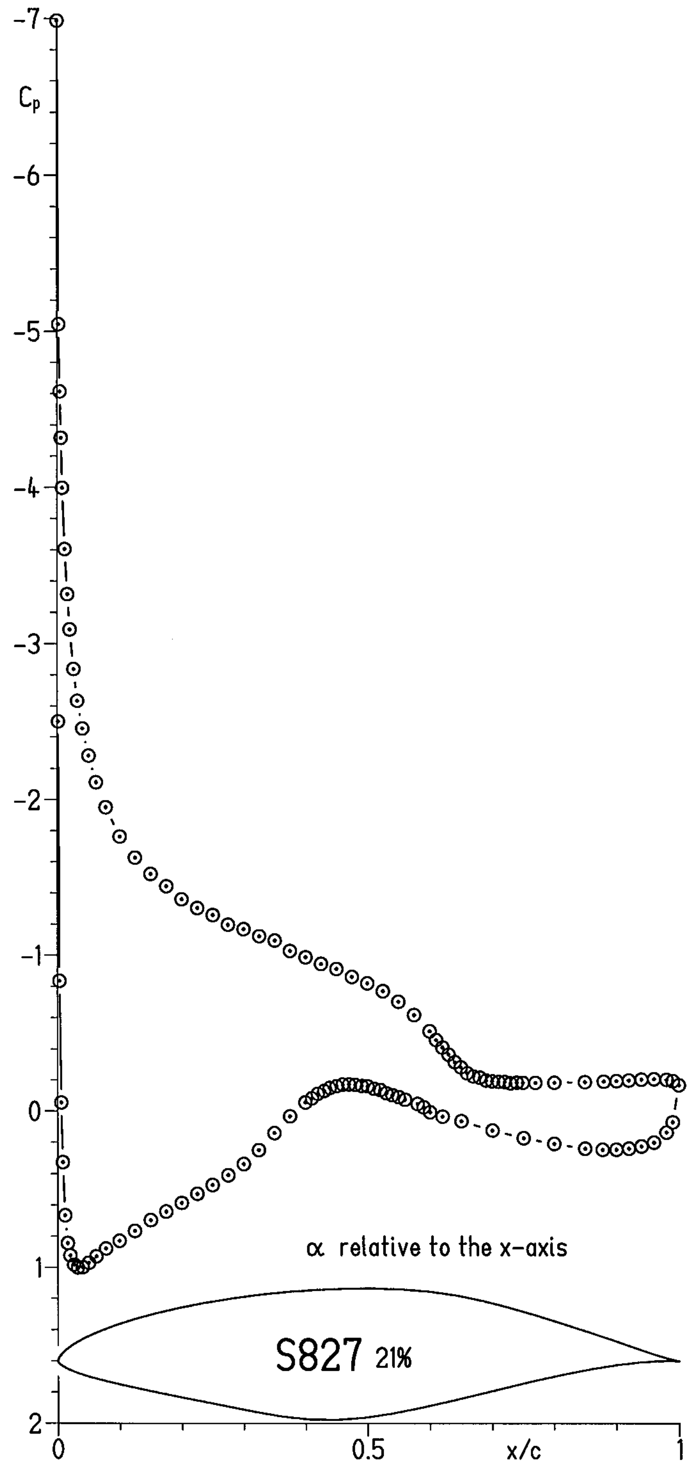
(l) $\alpha = 11.07°$.

Figure 5.- Continued.



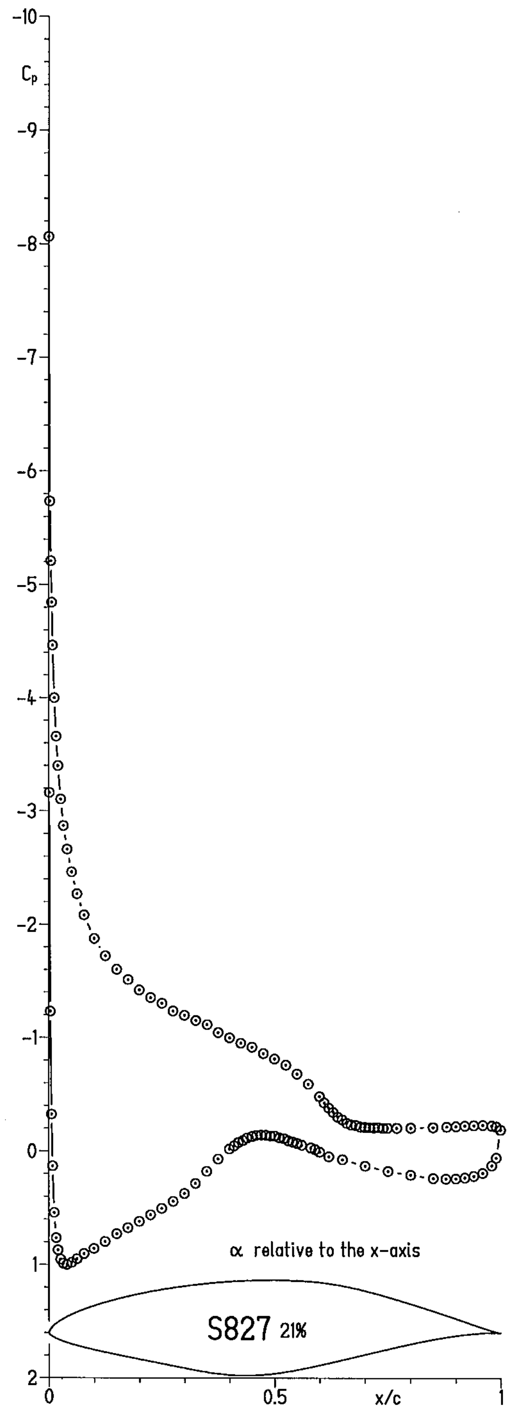
(m) $\alpha = 12.06°$.

Figure 5.- Continued.



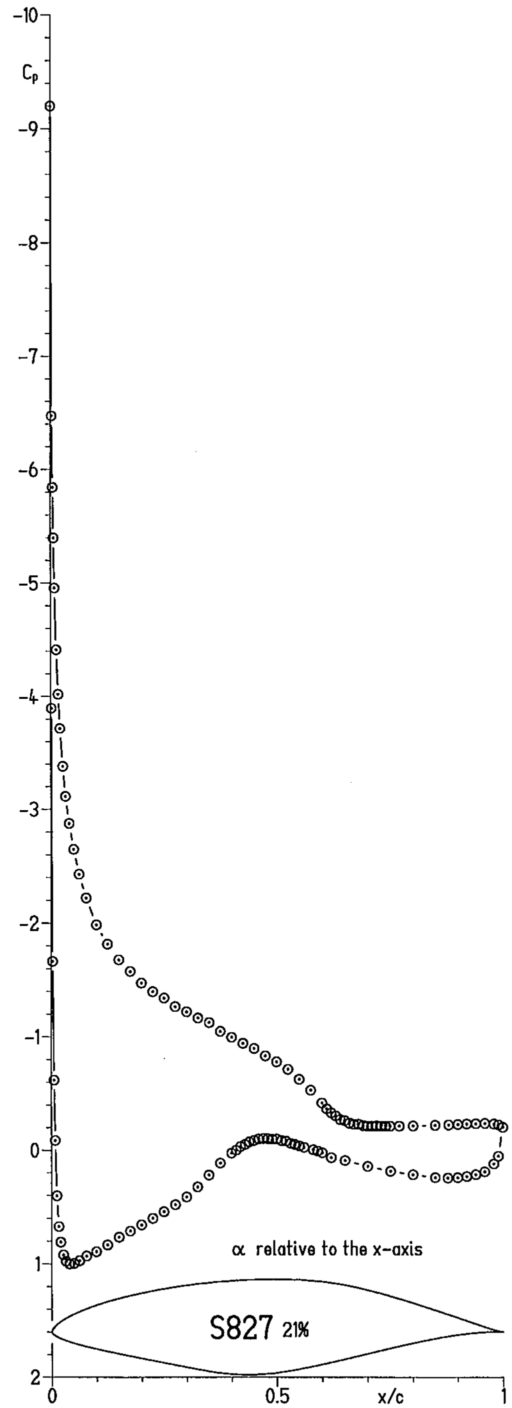
(n) $\alpha = 13.08°$.

Figure 5.- Continued.



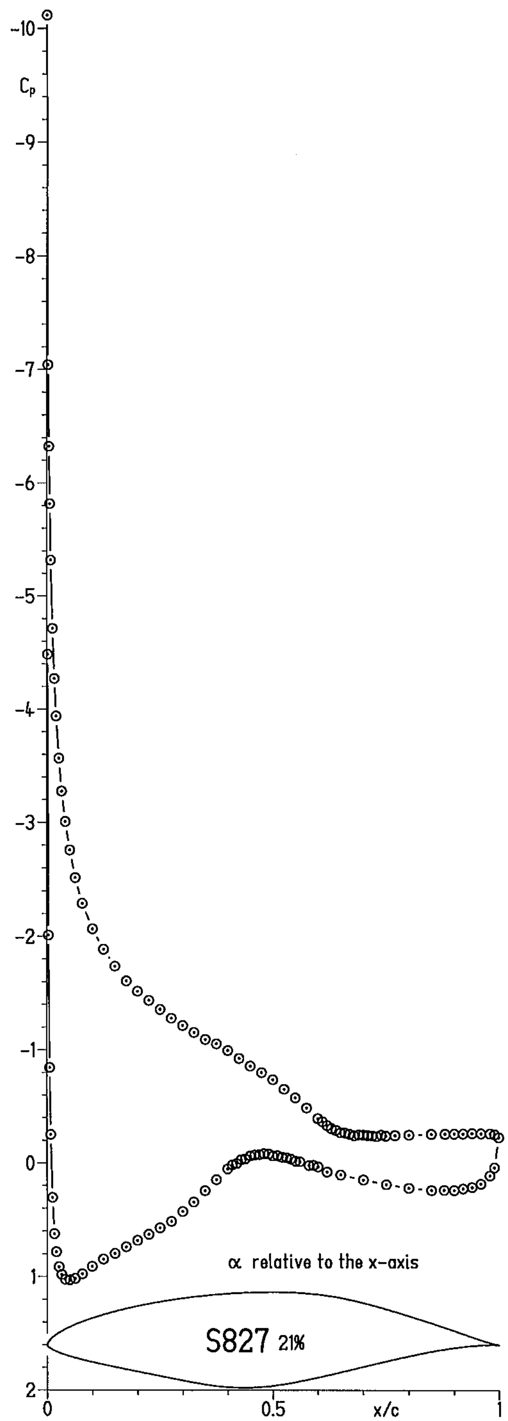
(o) $\alpha = 14.08°$.

Figure 5.- Continued.



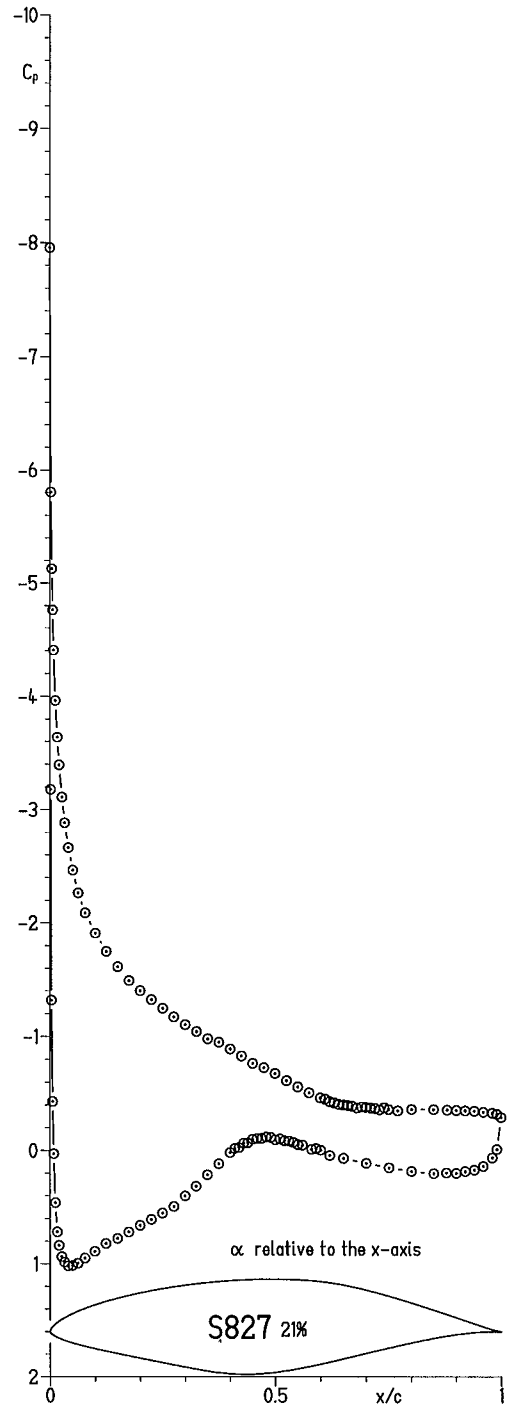
(p) $\alpha = 15.09°$.

Figure 5.- Continued.



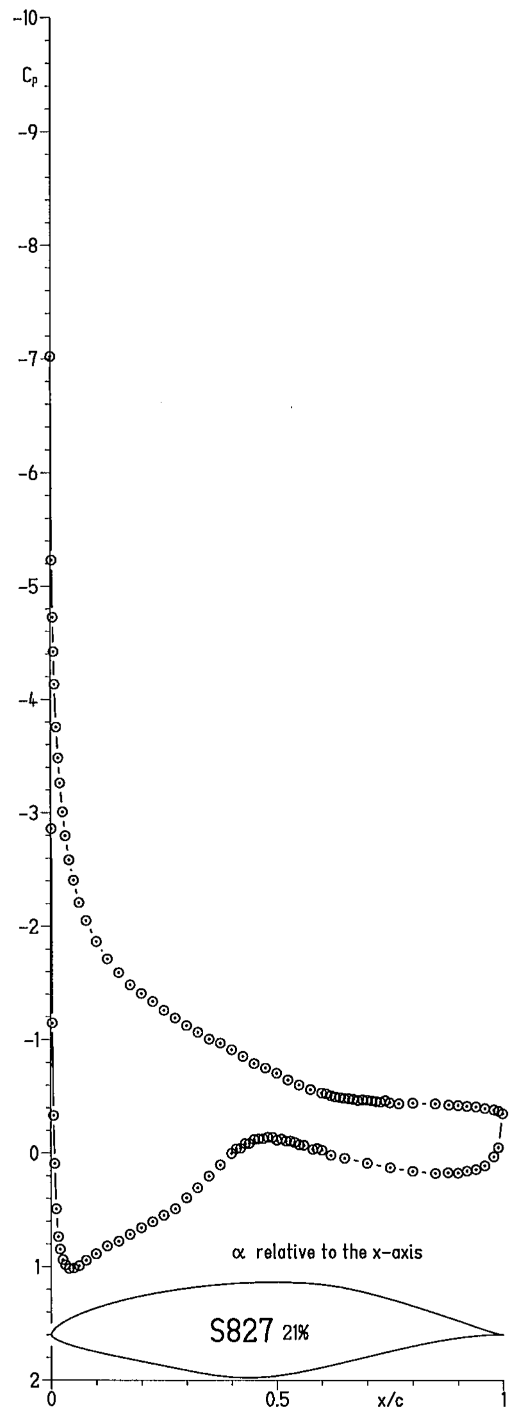
(q) $\alpha = 16.07°$.

Figure 5.- Continued.



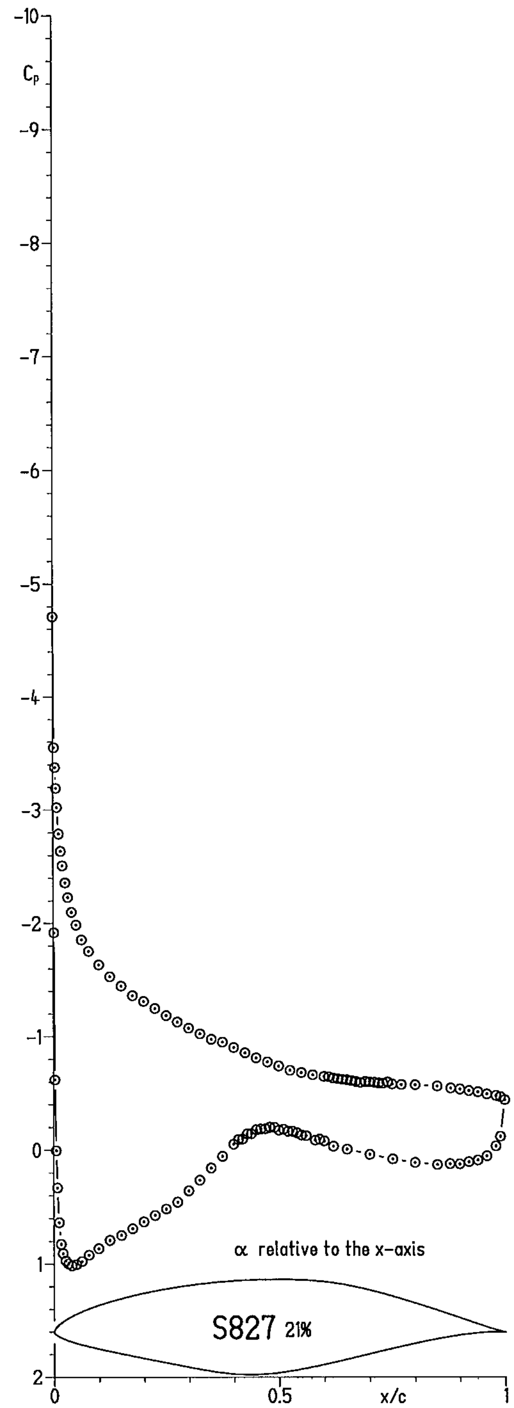
(r) α = 17.07°.

Figure 5.- Continued.



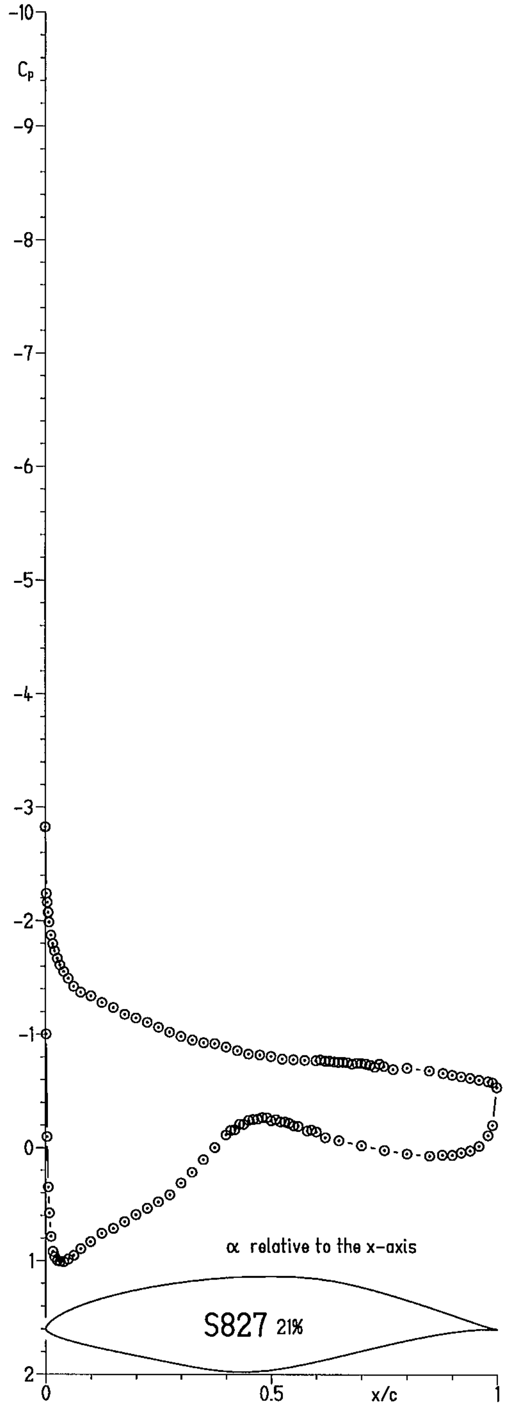
(s) $\alpha = 18.07°$.

Figure 5.- Continued.



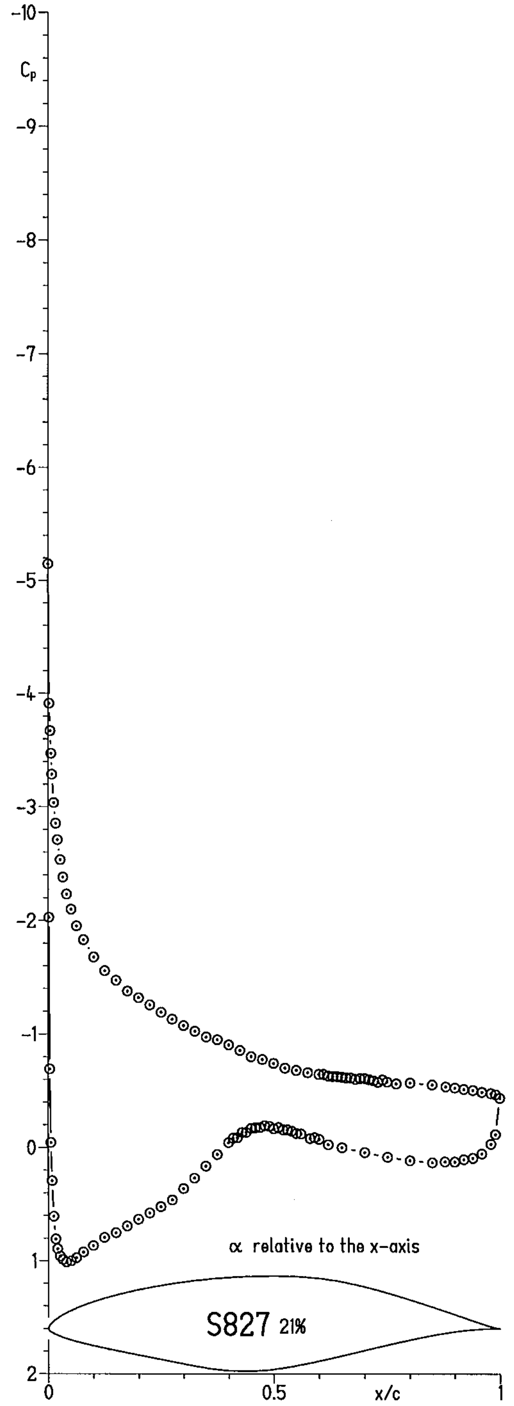
(t) $\alpha = 19.10°$.

Figure 5.- Continued.



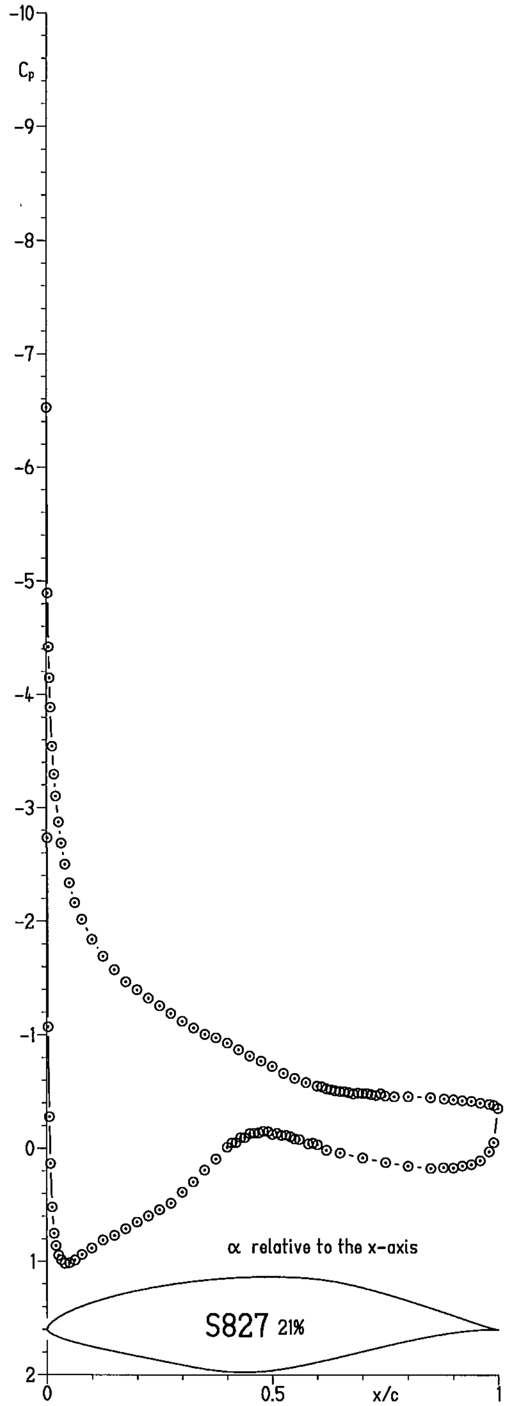
(u) $\alpha = 20.04°$.

Figure 5.- Continued.



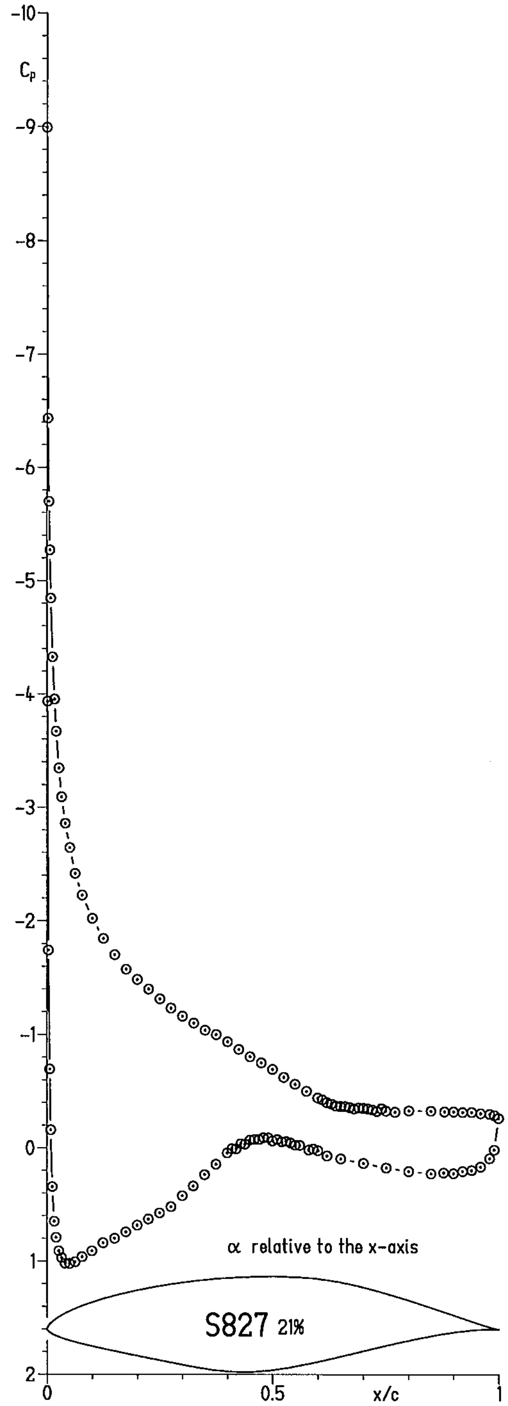
(v) $\alpha = 19.06°$.

Figure 5.- Continued.



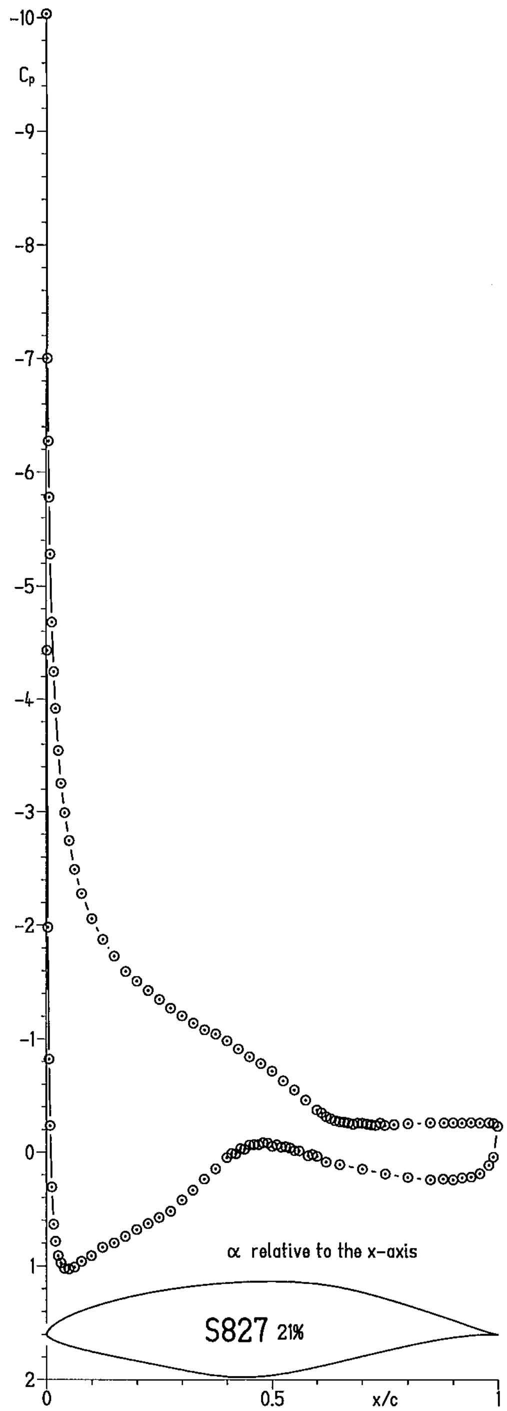
(w) $\alpha = 18.05°$.

Figure 5.- Continued.



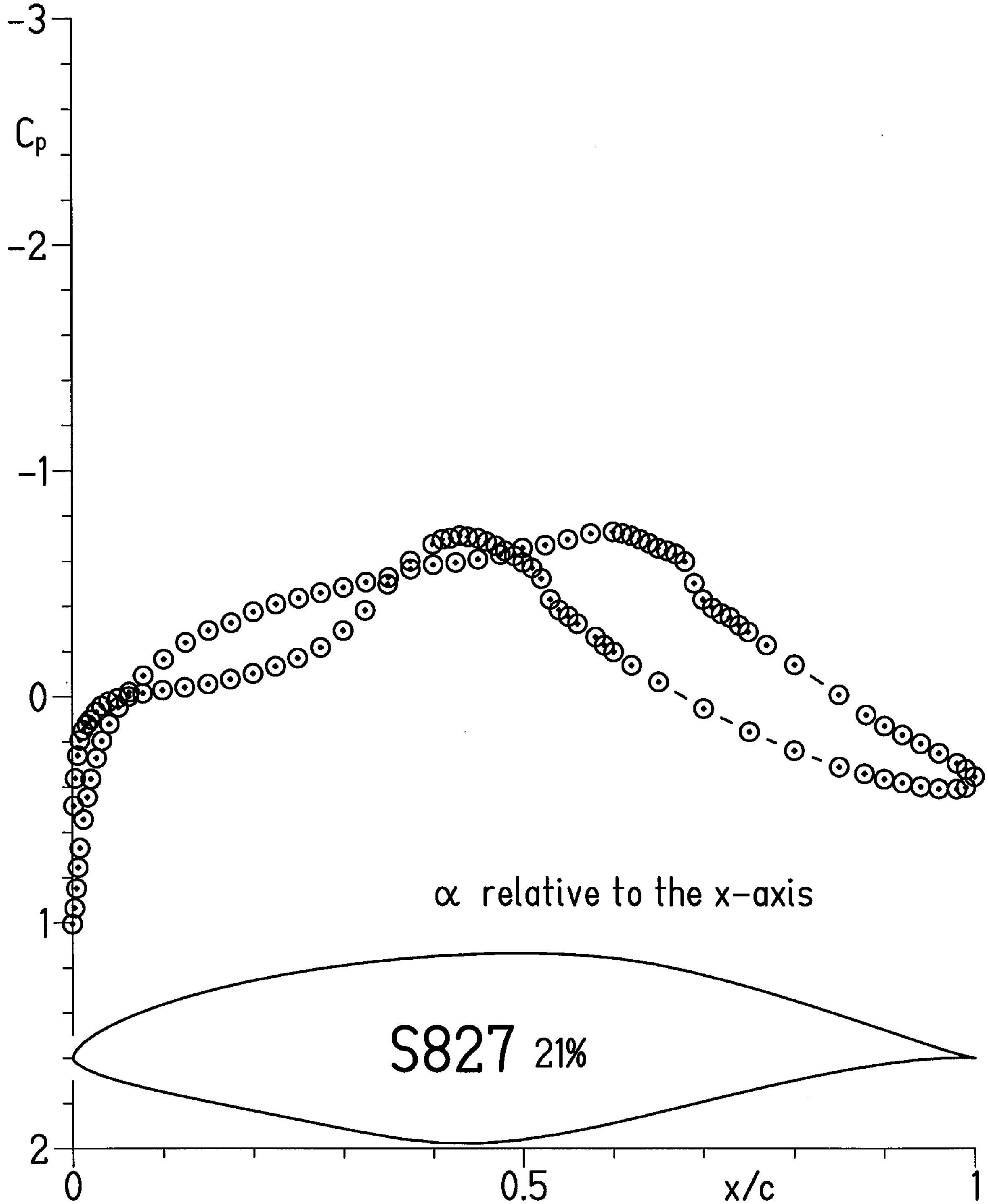
(x) $\alpha = 17.07°$.

Figure 5.- Continued.



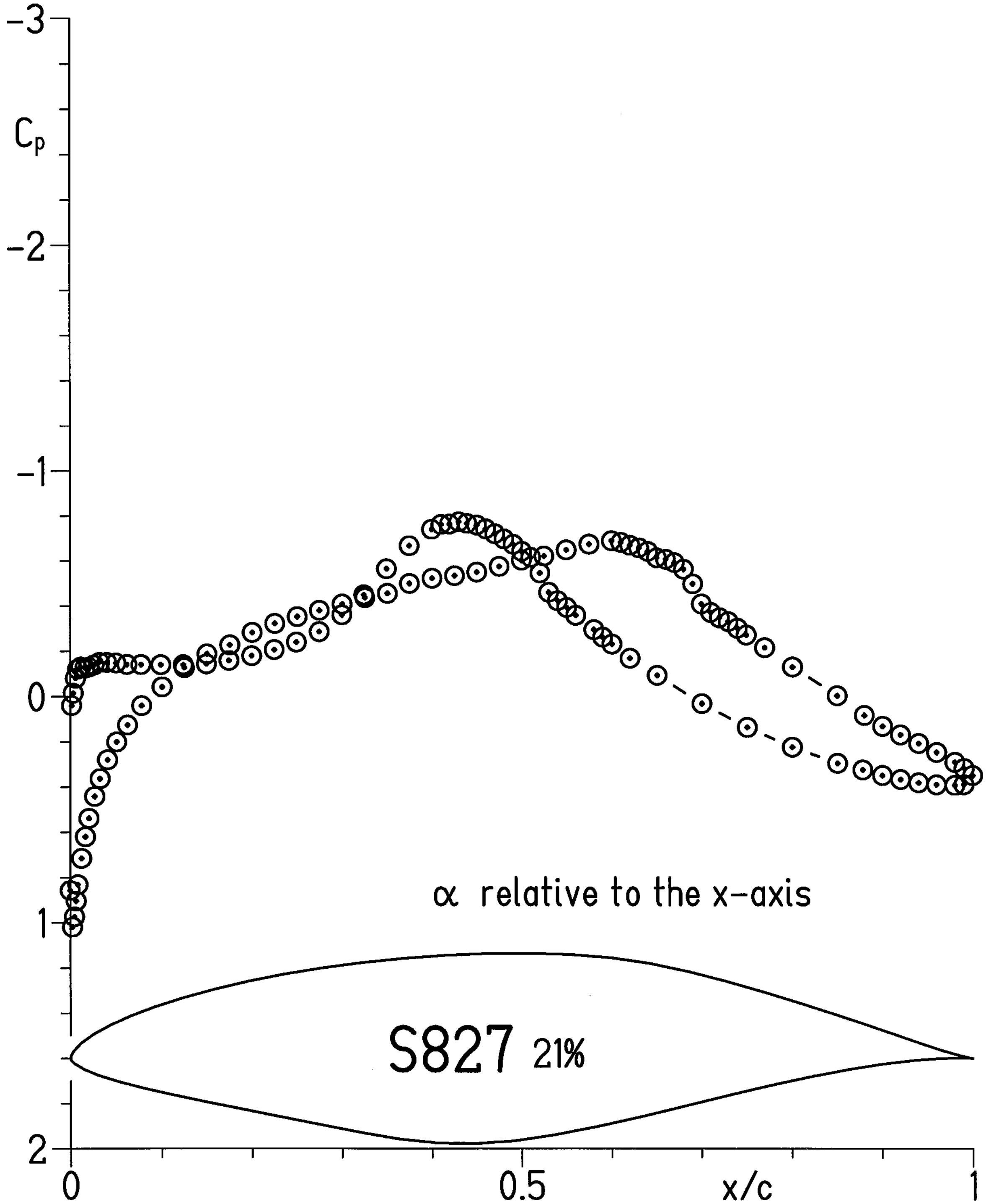
(y) $\alpha = 16.08°$.

Figure 5.- Continued.



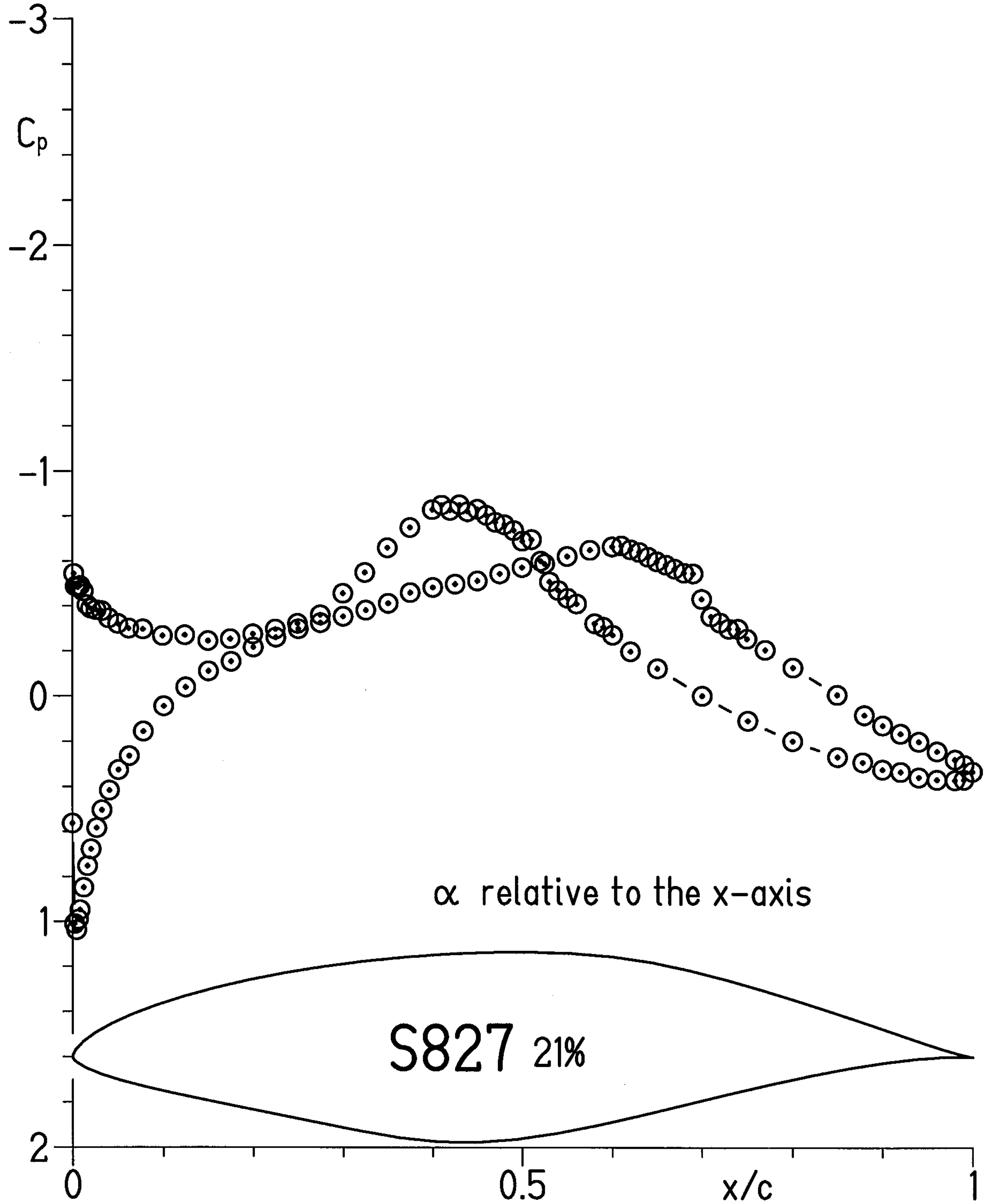
(z) $\alpha = -1.00°$.

Figure 5.- Continued.



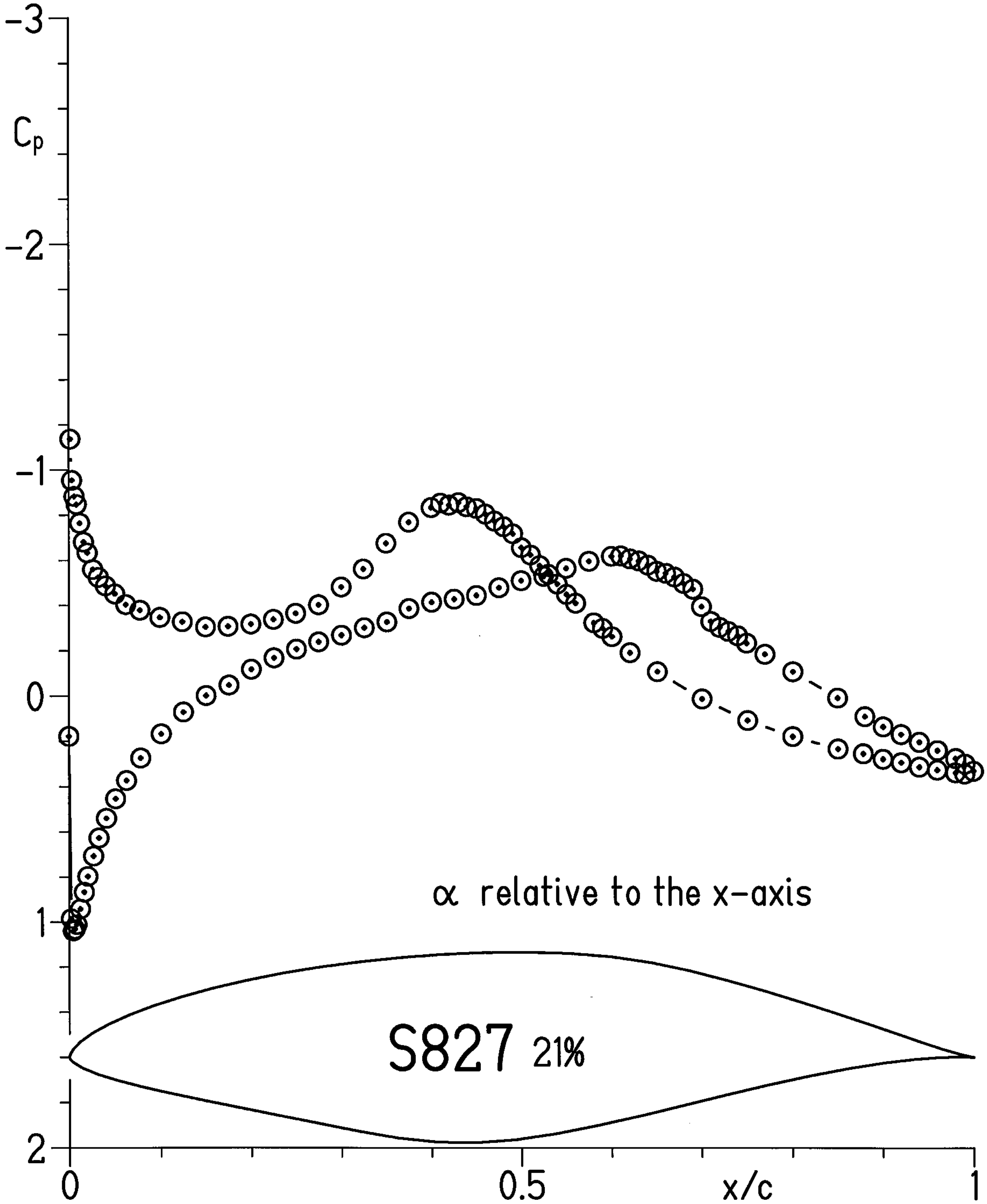
(aa) $\alpha = -2.01°$.

Figure 5.- Continued.



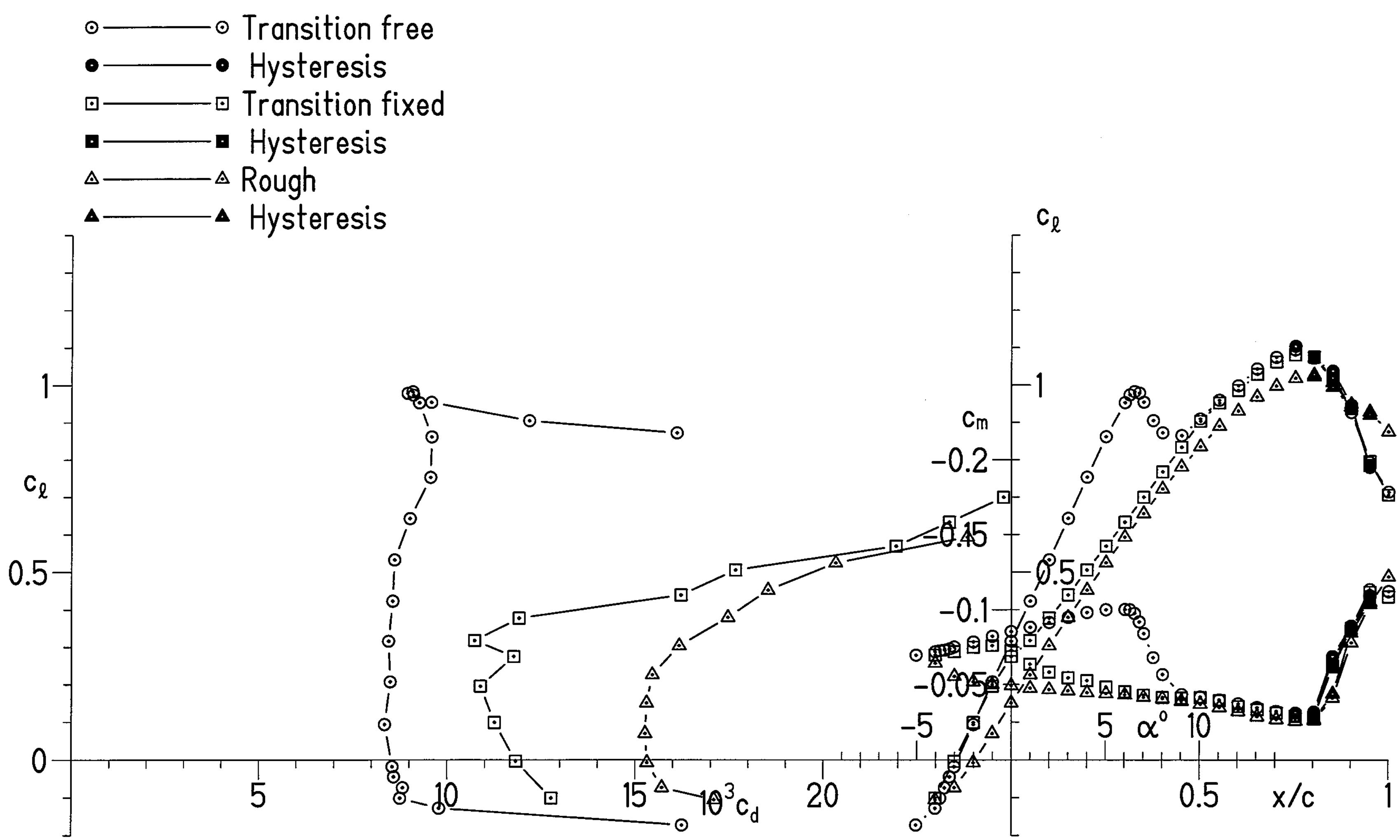
(bb) $\alpha = -3.01°$.

Figure 5.- Continued.



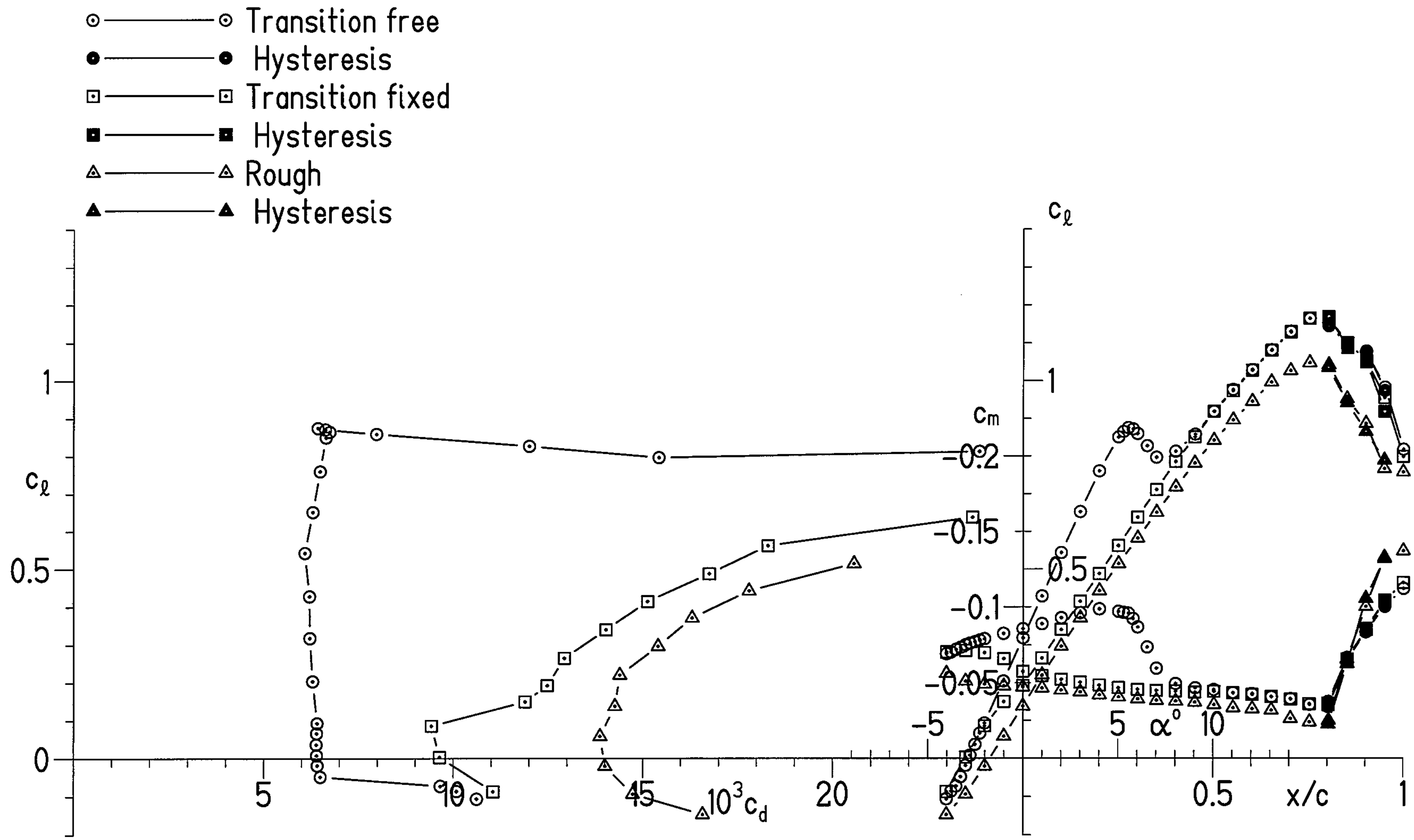
(cc) $\alpha = -4.02°$.

Figure 5.- Concluded.



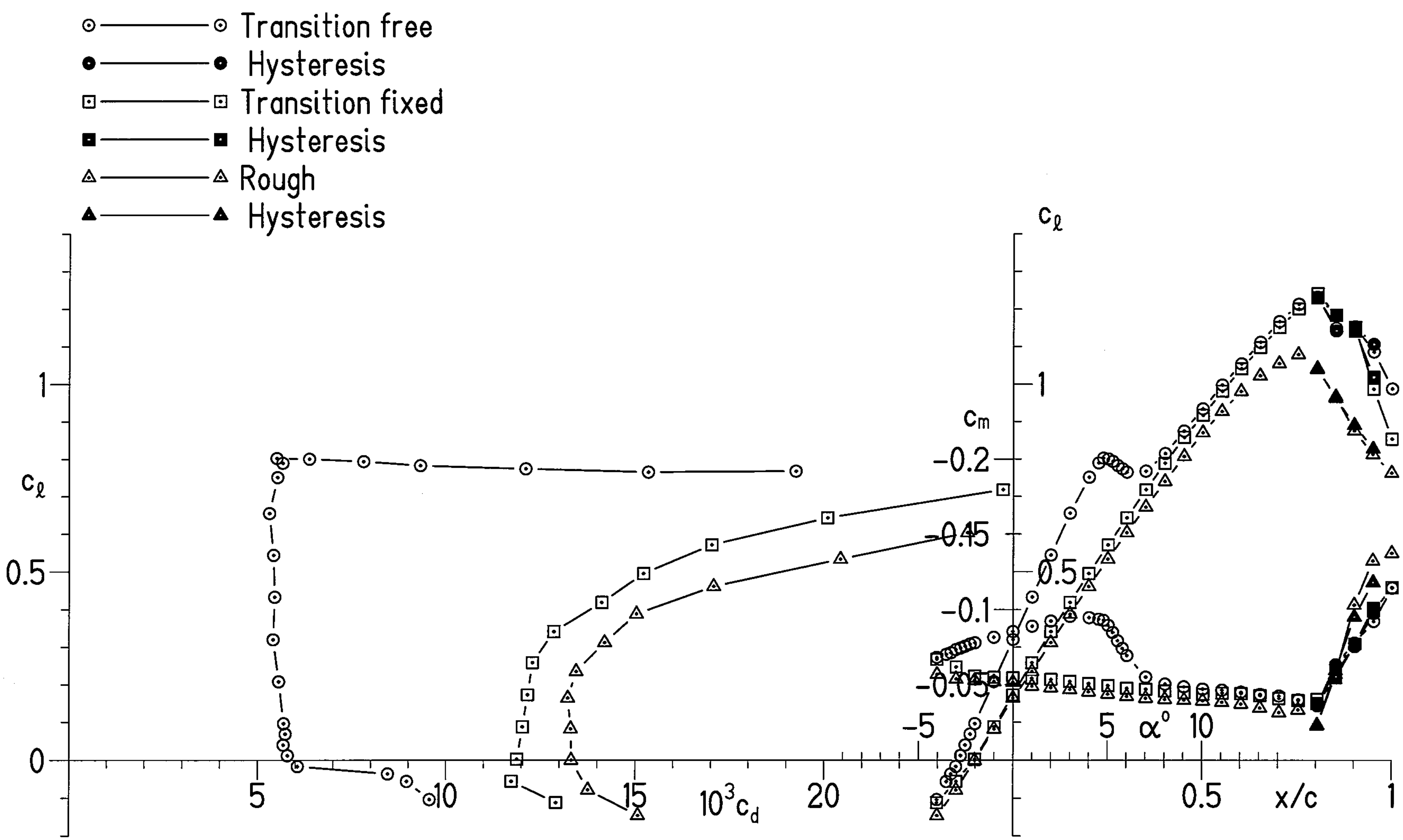
(a) $R = 1 \times 10^6$.

Figure 6.- Section characteristics with transition free, transition fixed, and rough.



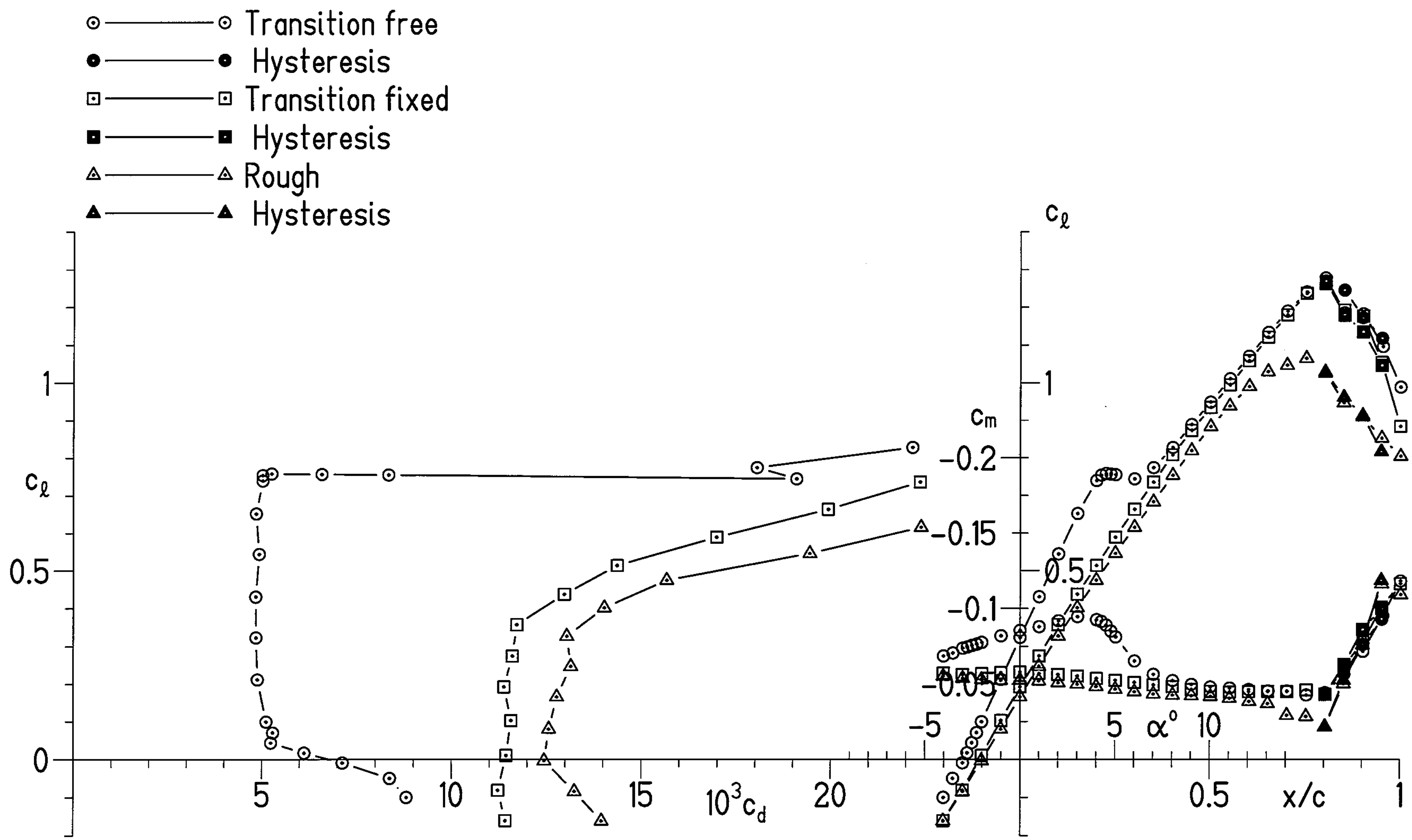
(b) $R = 2 \times 10^6$.

Figure 6.- Continued.



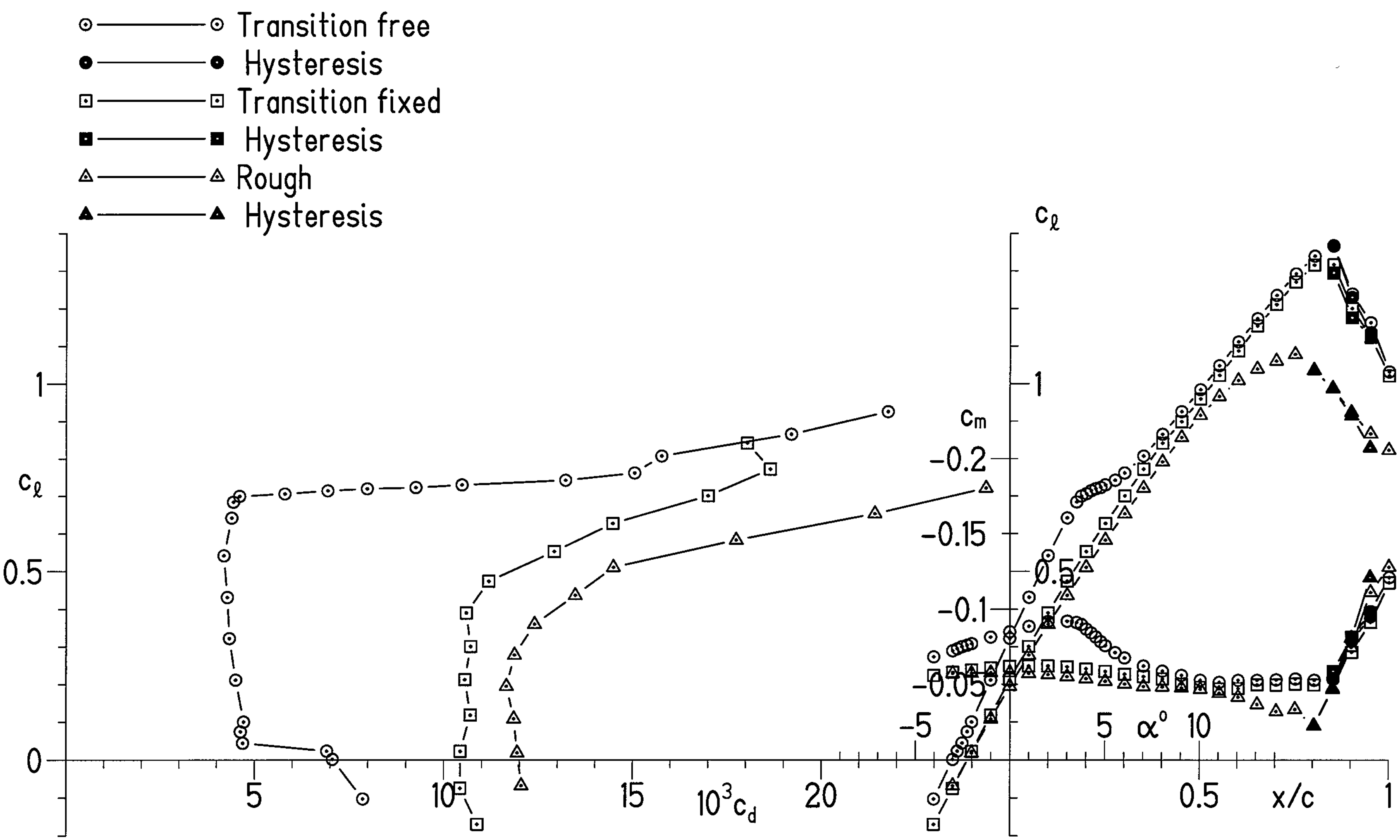
(c) $R = 3 \times 10^6$.

Figure 6.- Continued.



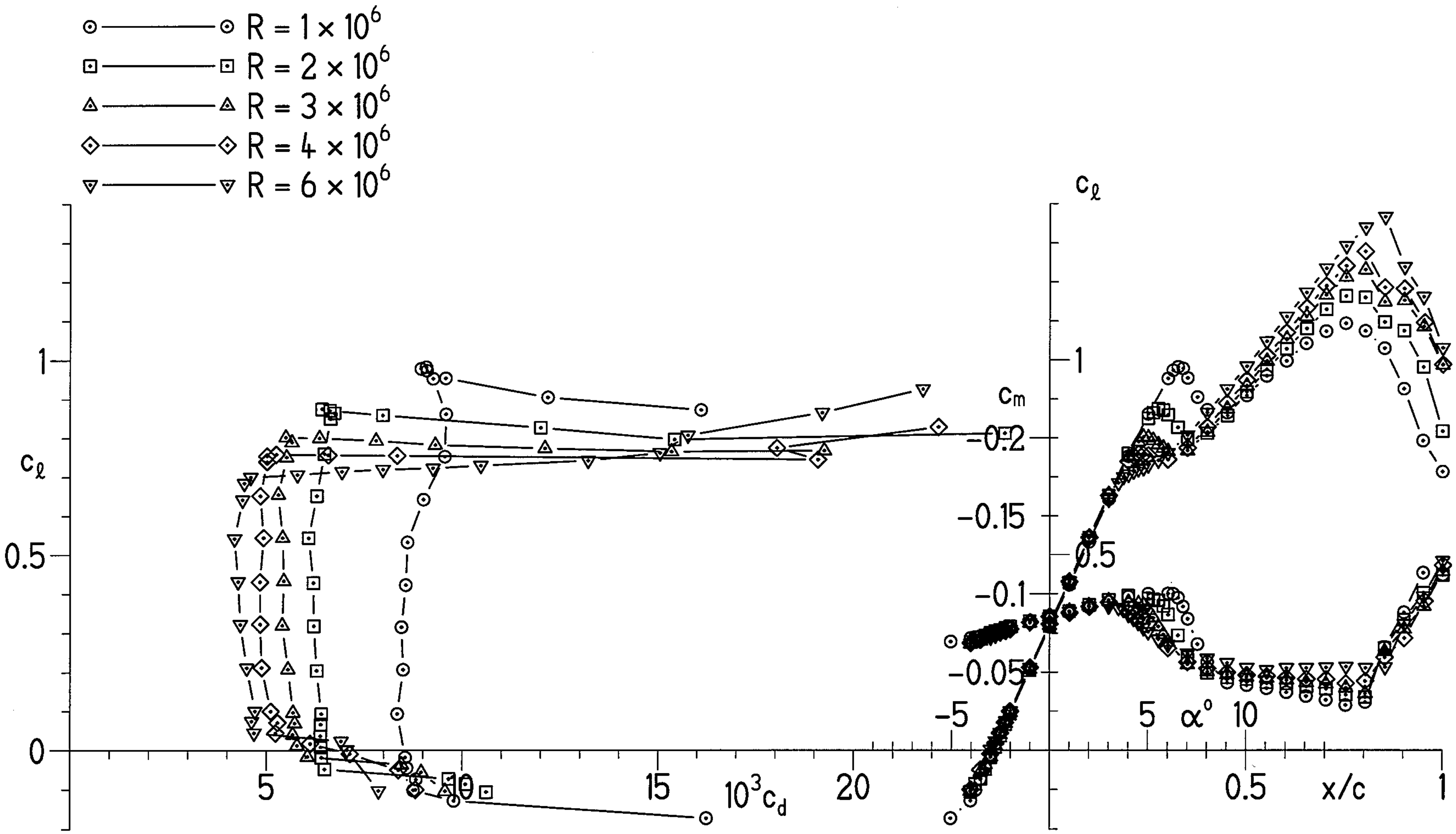
(d) $R = 4 \times 10^6$.

Figure 6.- Continued.



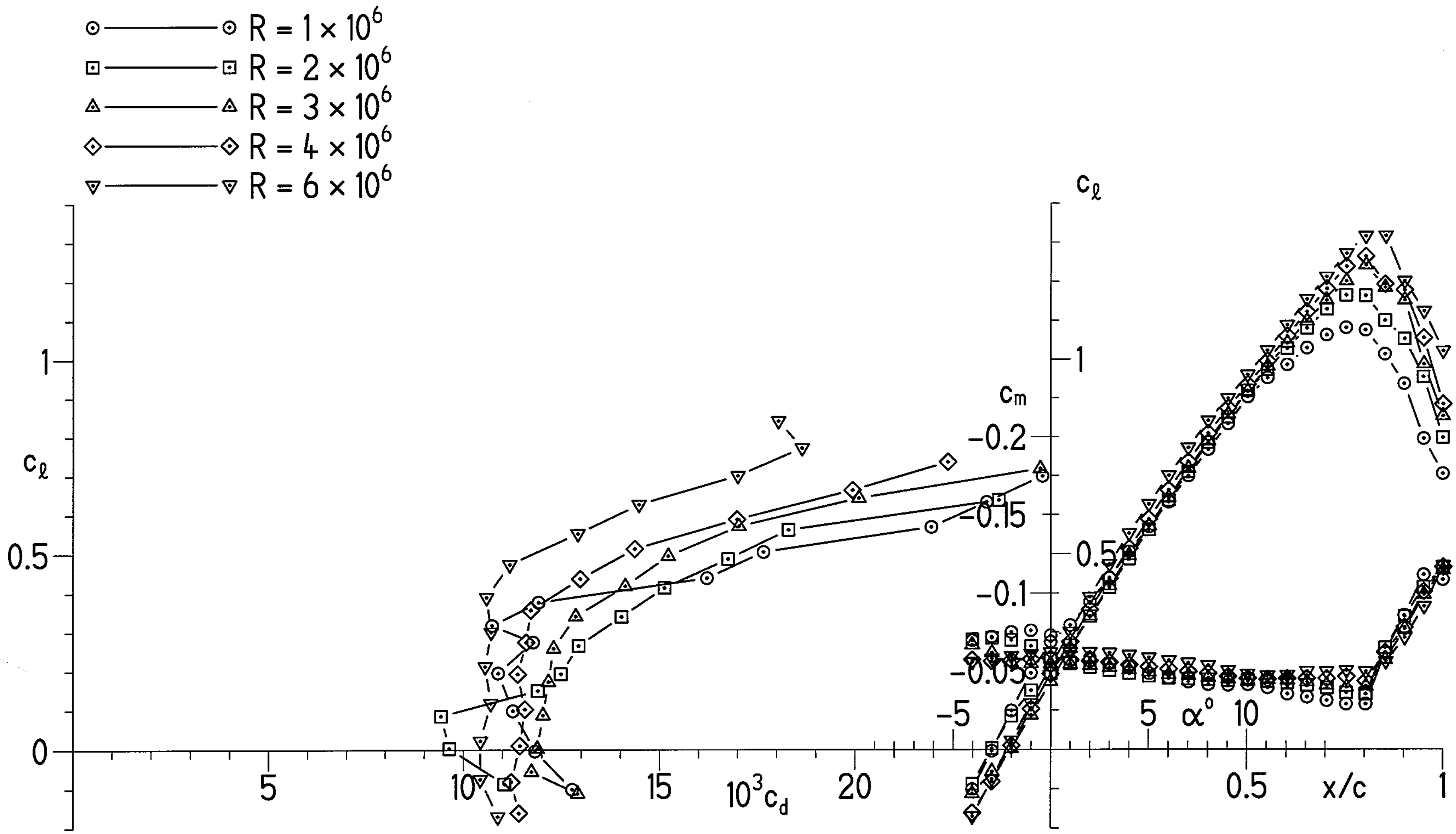
(e) $R = 6 \times 10^6$.

Figure 6.- Concluded.



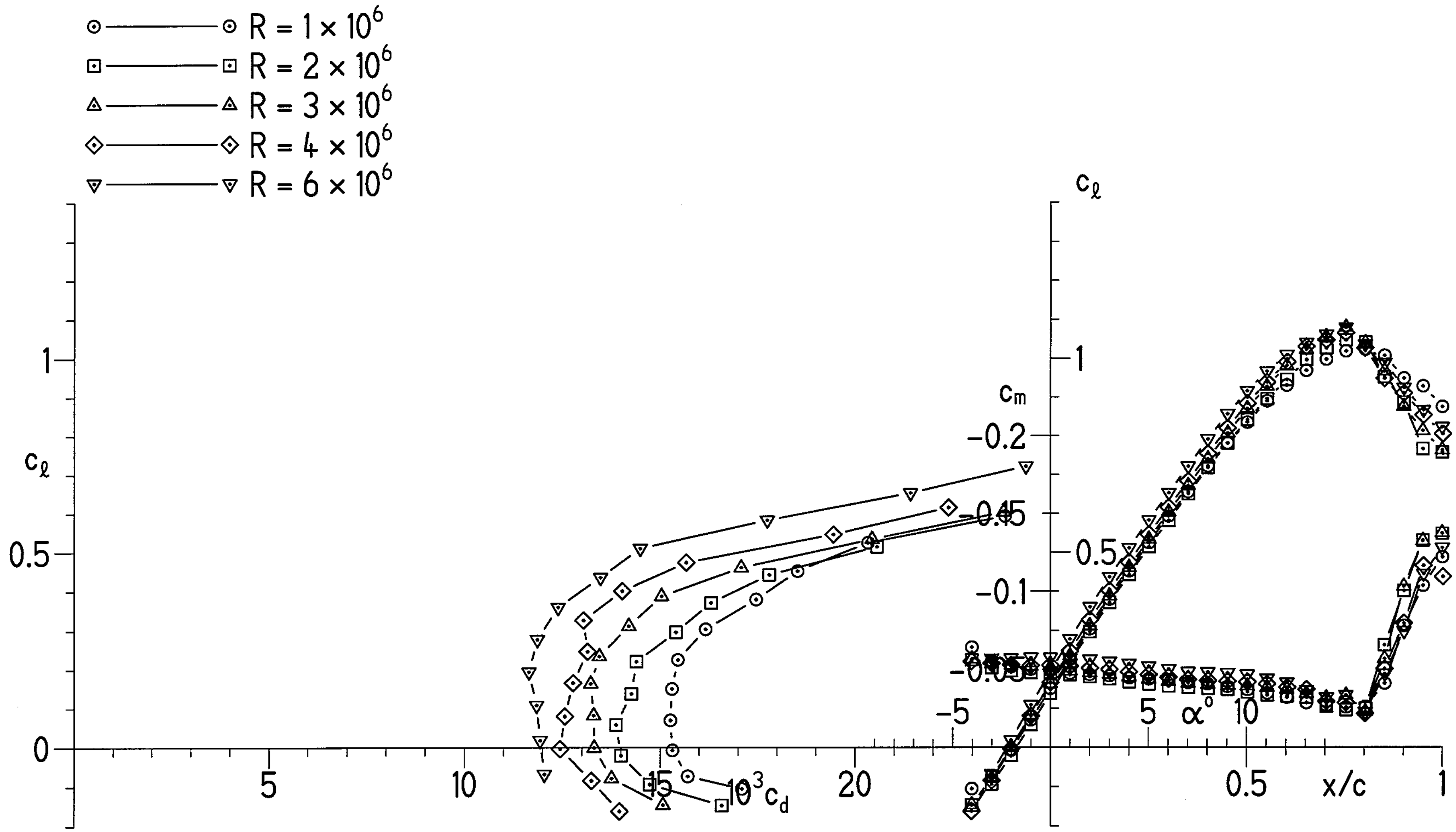
(a) Transition free.

Figure 7.- Effects of Reynolds number on section characteristics.



(b) Transition fixed.

Figure 7.- Continued.



(c) Rough.

Figure 7.- Concluded.

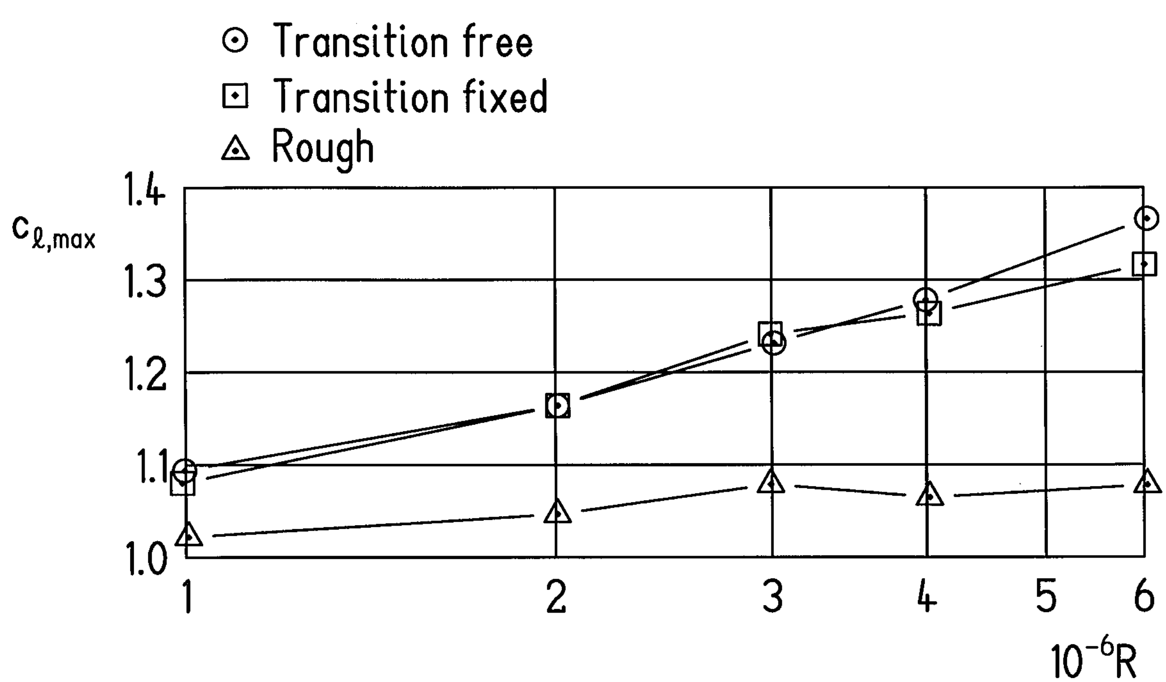


Figure 8.- Variation of maximum lift coefficient with Reynolds number.

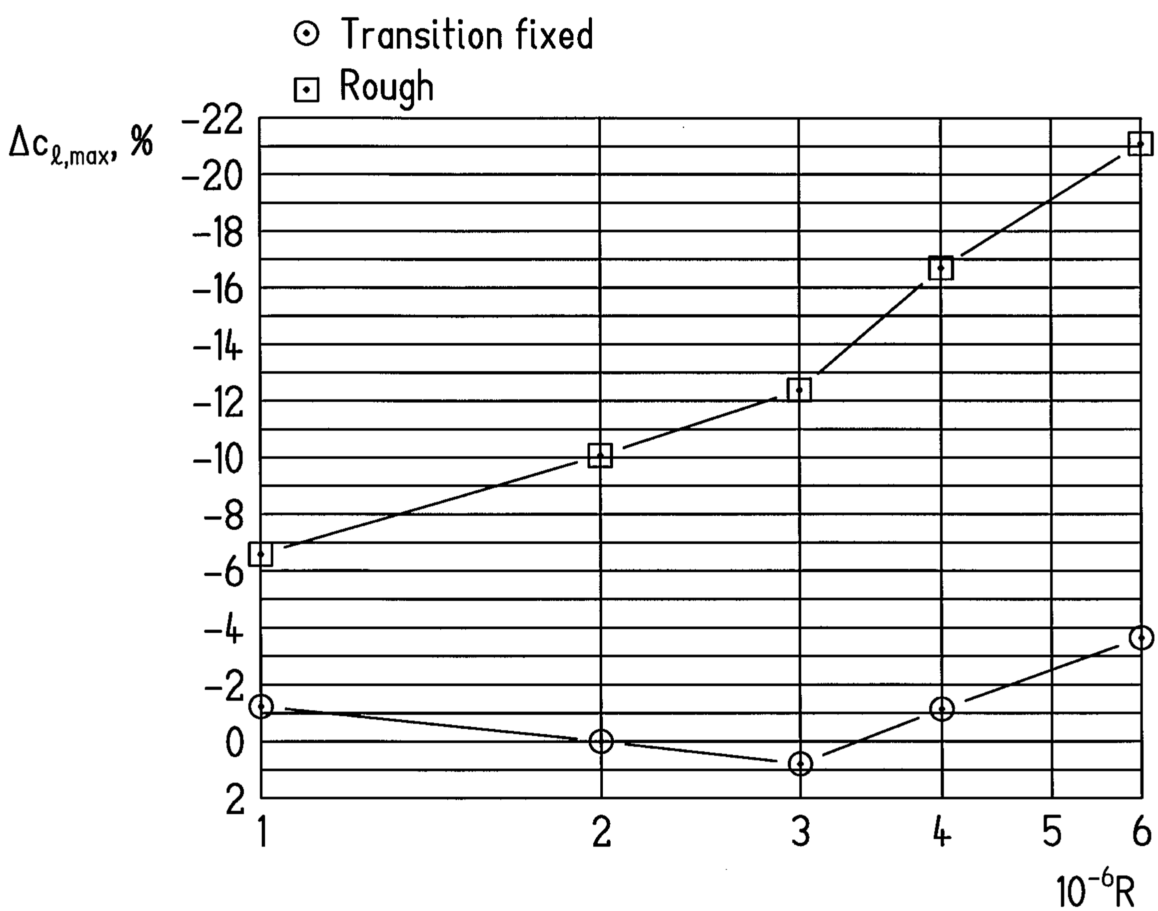


Figure 9.- Variation of change in maximum lift coefficient due to leading-edge roughness with Reynolds number.

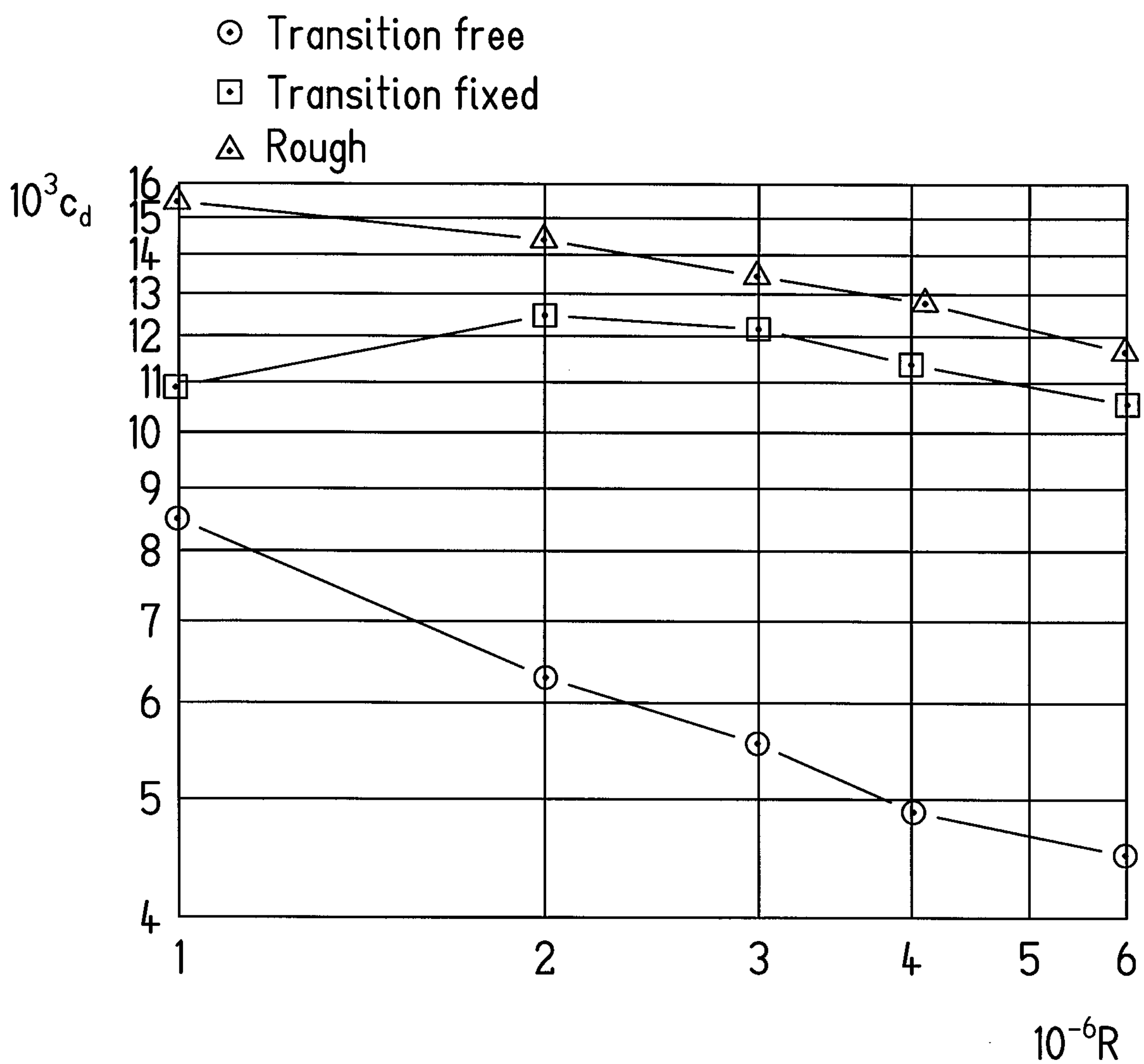
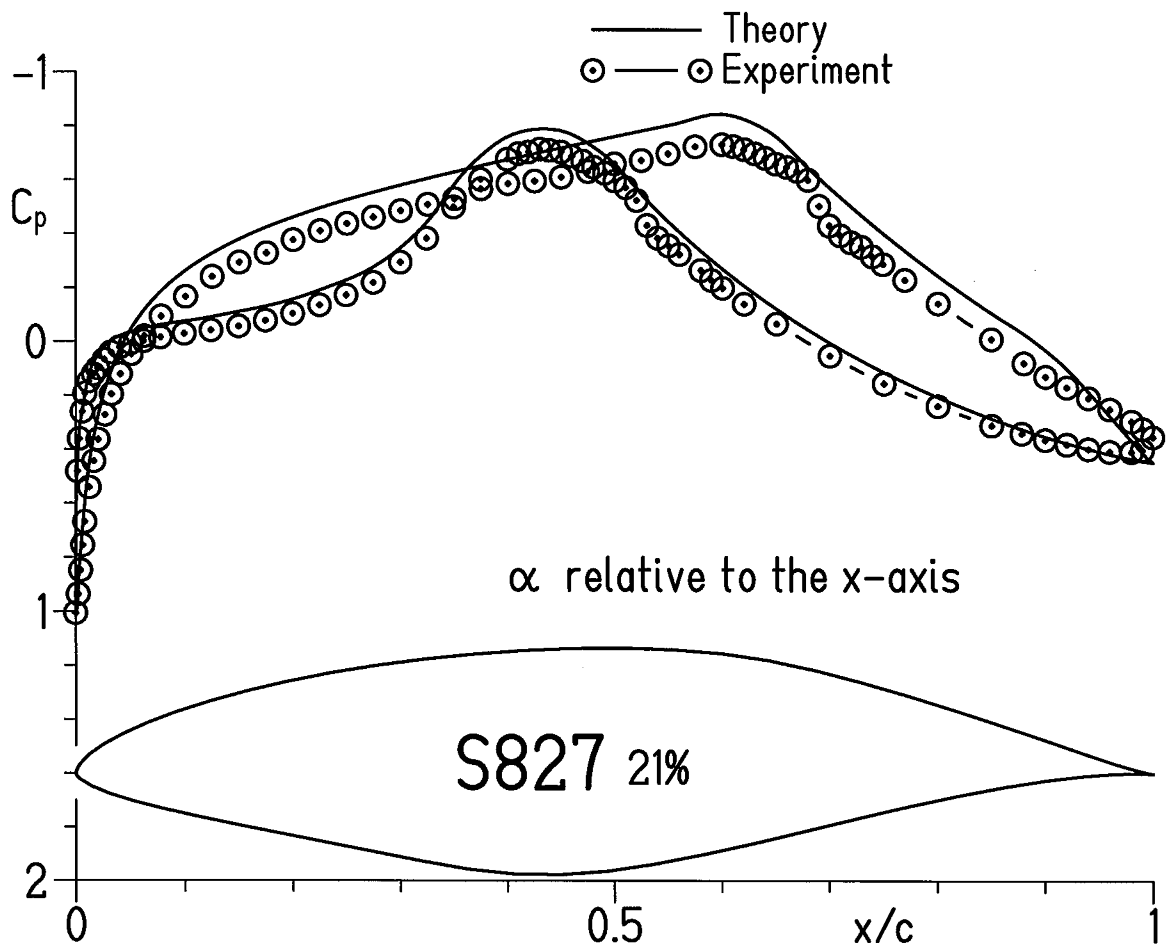
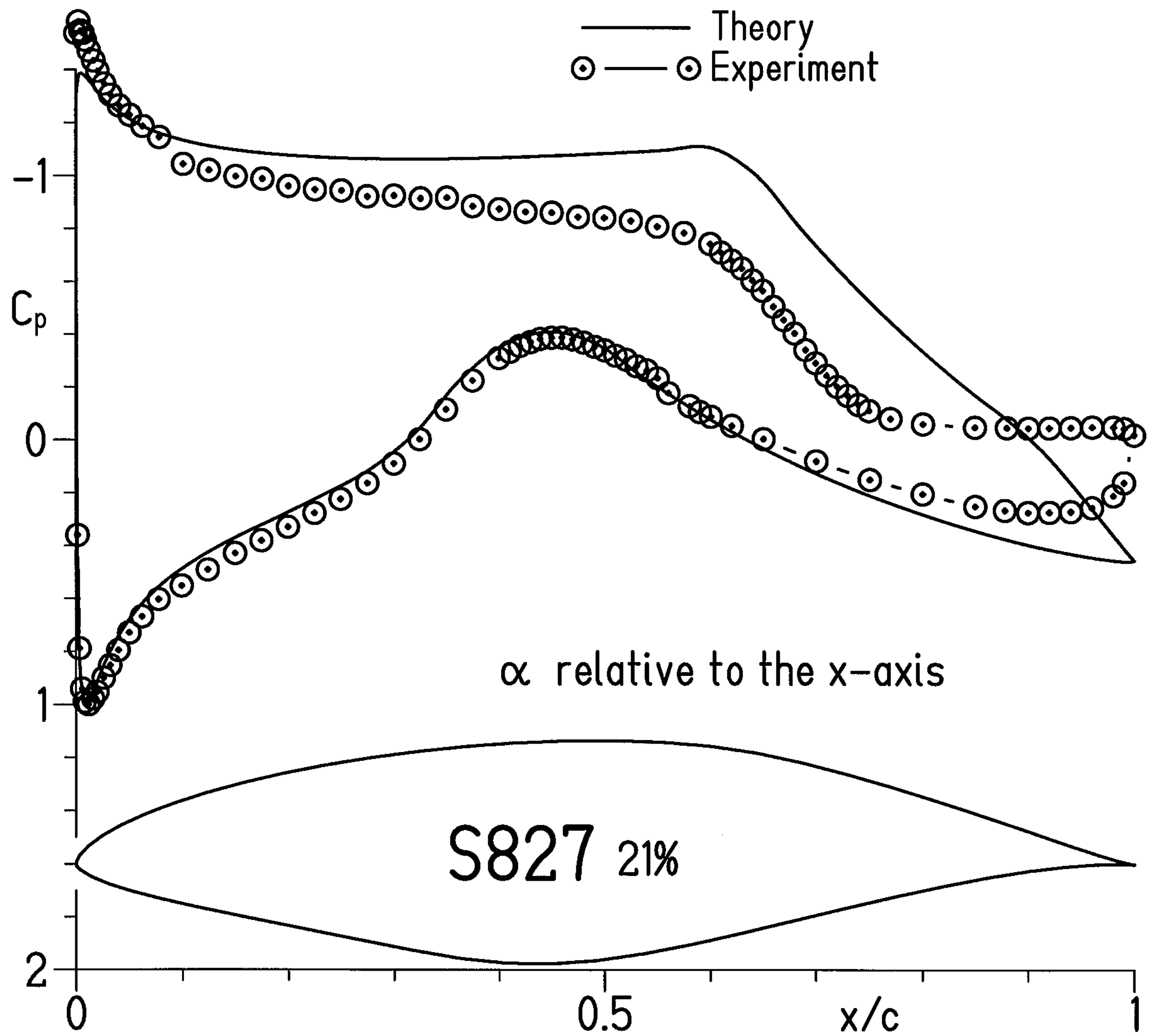


Figure 10.- Variation of profile-drag coefficient at $c_l = 0.2$ with Reynolds number.



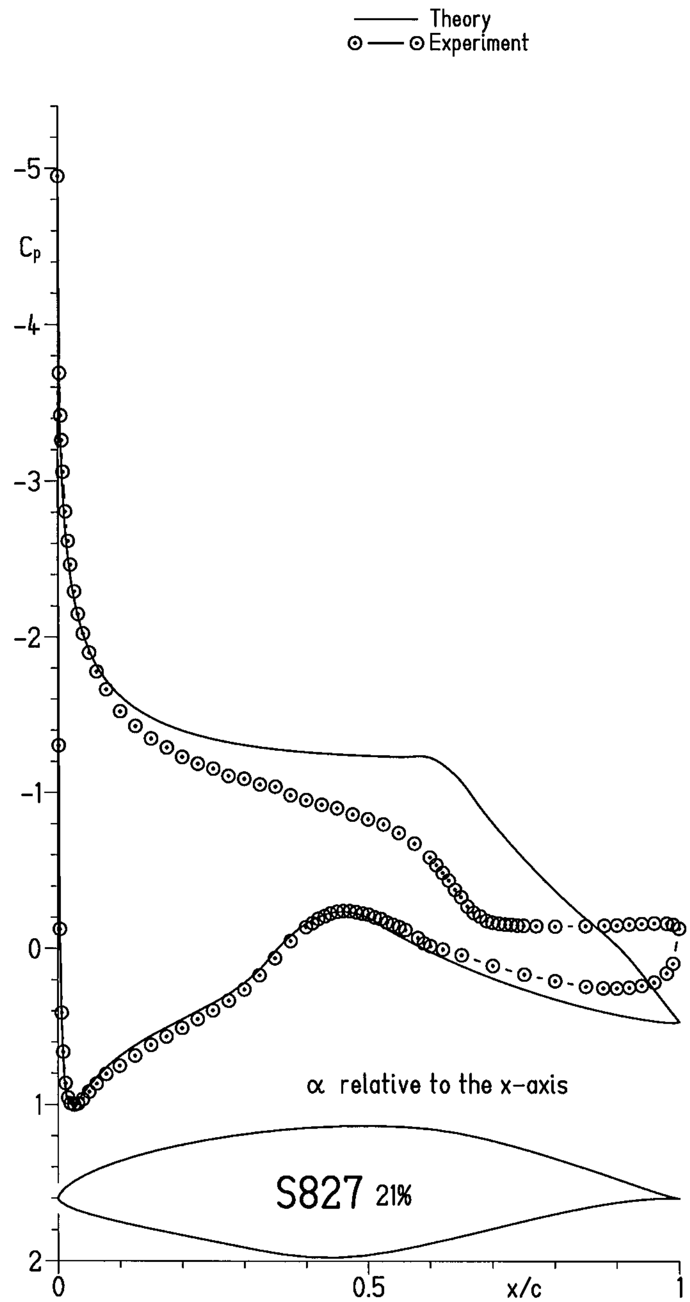
(a) $c_l = 0.21$.

Figure 11.- Comparison of theoretical and experimental pressure distributions.



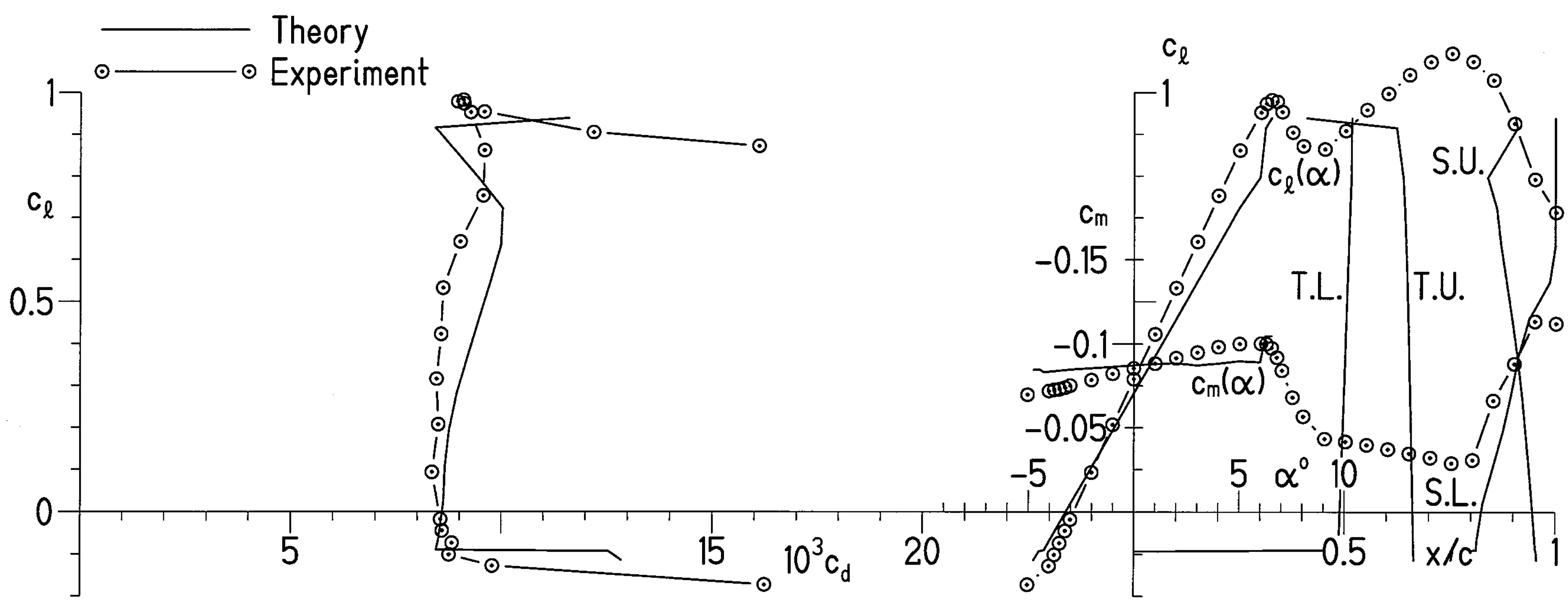
(b) $c_l = 0.77$.

Figure 11.- Continued.



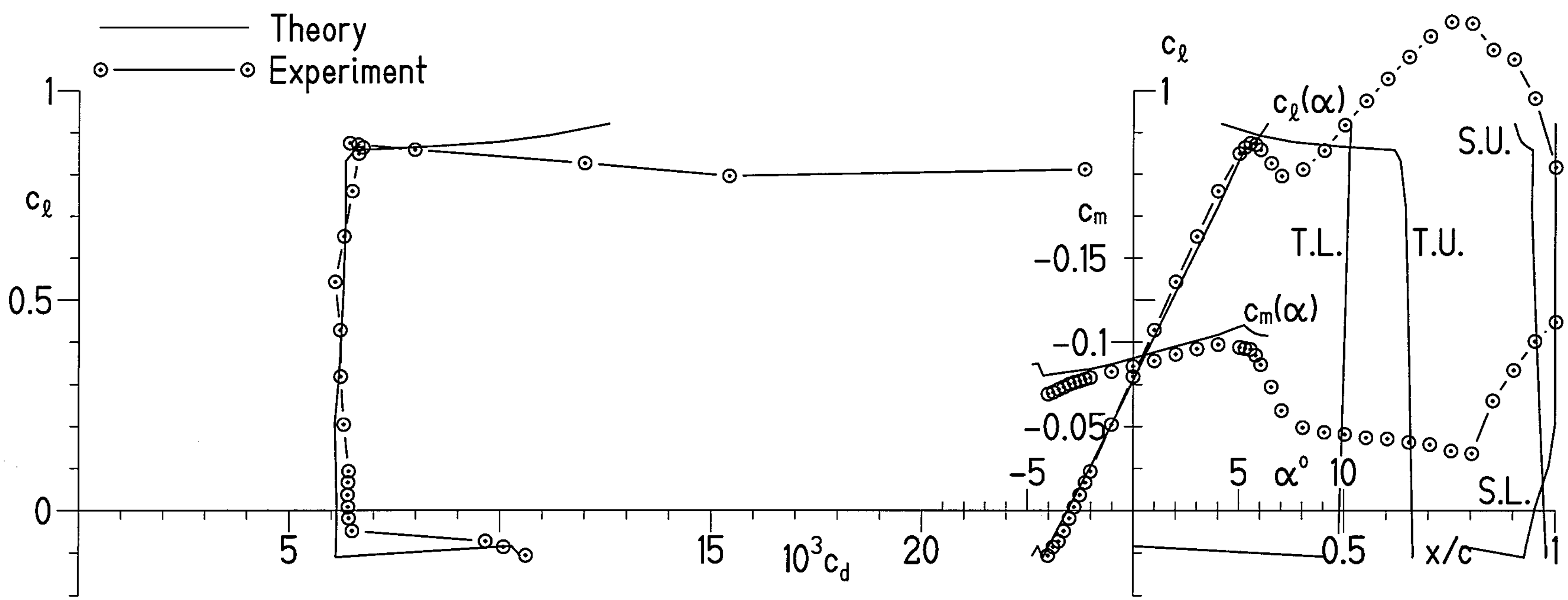
(c) $c_l = 1.01$.

Figure 11.- Concluded.



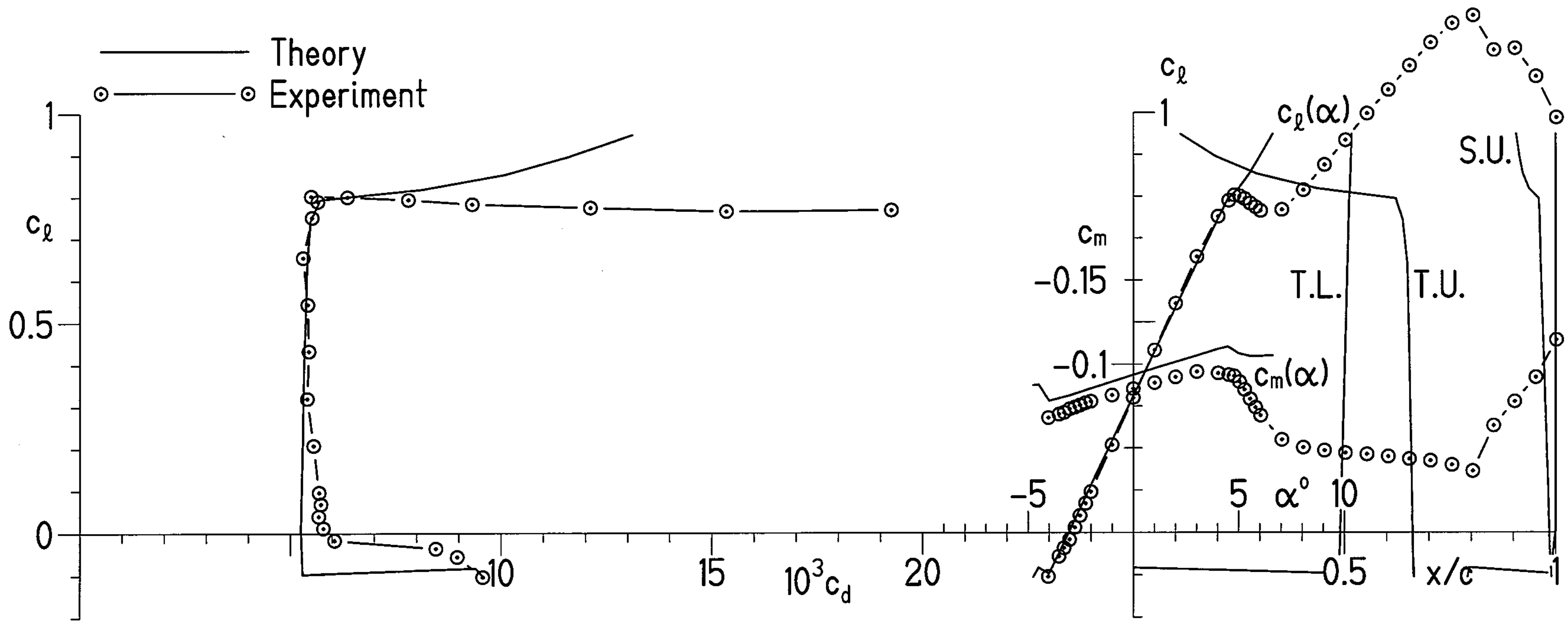
(a) $R = 1 \times 10^6$.

Figure 12.- Comparison of theoretical and experimental section characteristics with transition free.



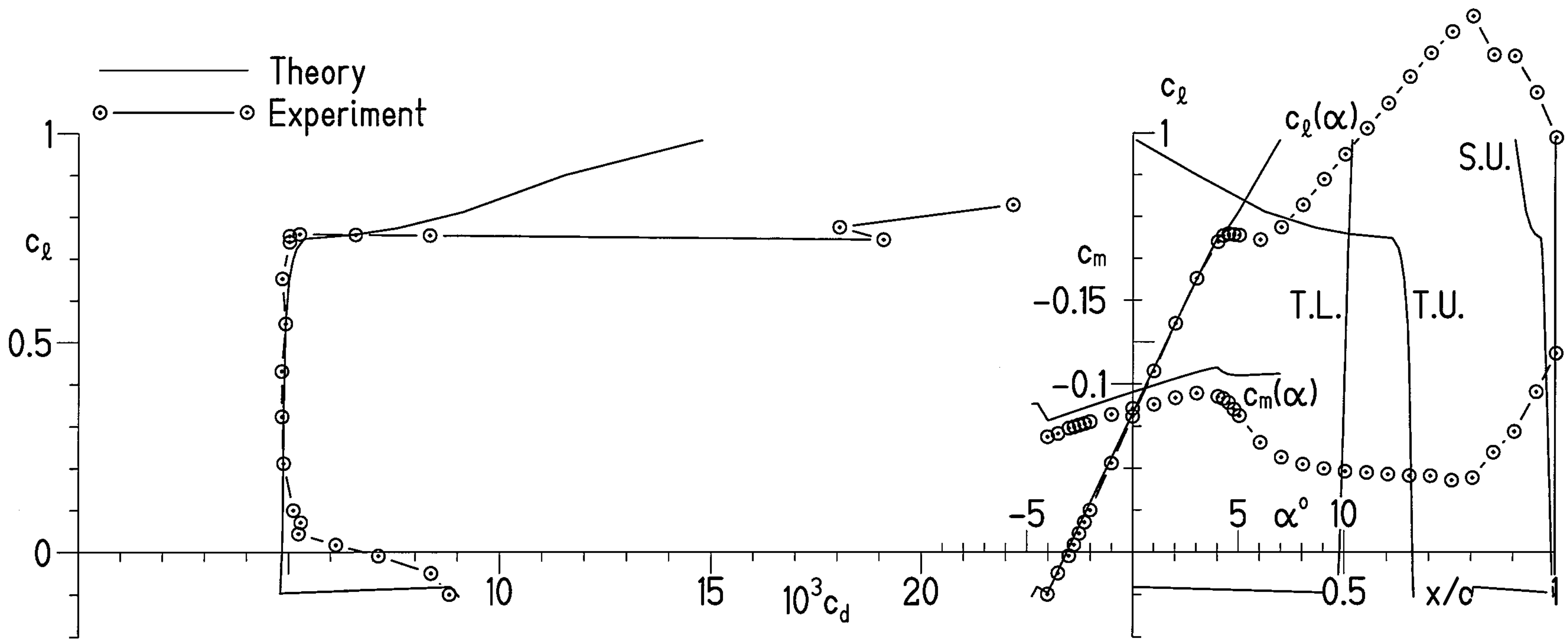
(b) $R = 2 \times 10^6$.

Figure 12.- Continued.



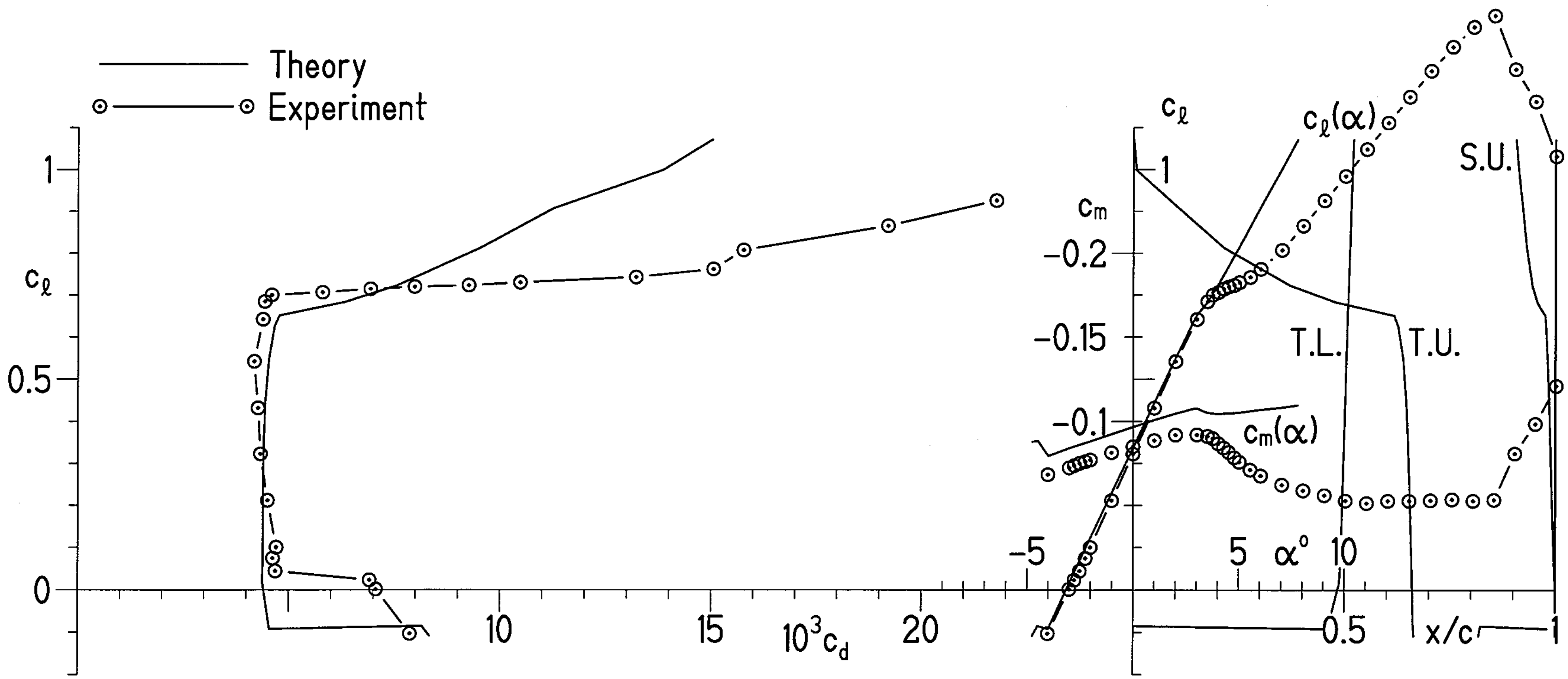
(c) $R = 3 \times 10^6$.

Figure 12.- Continued.



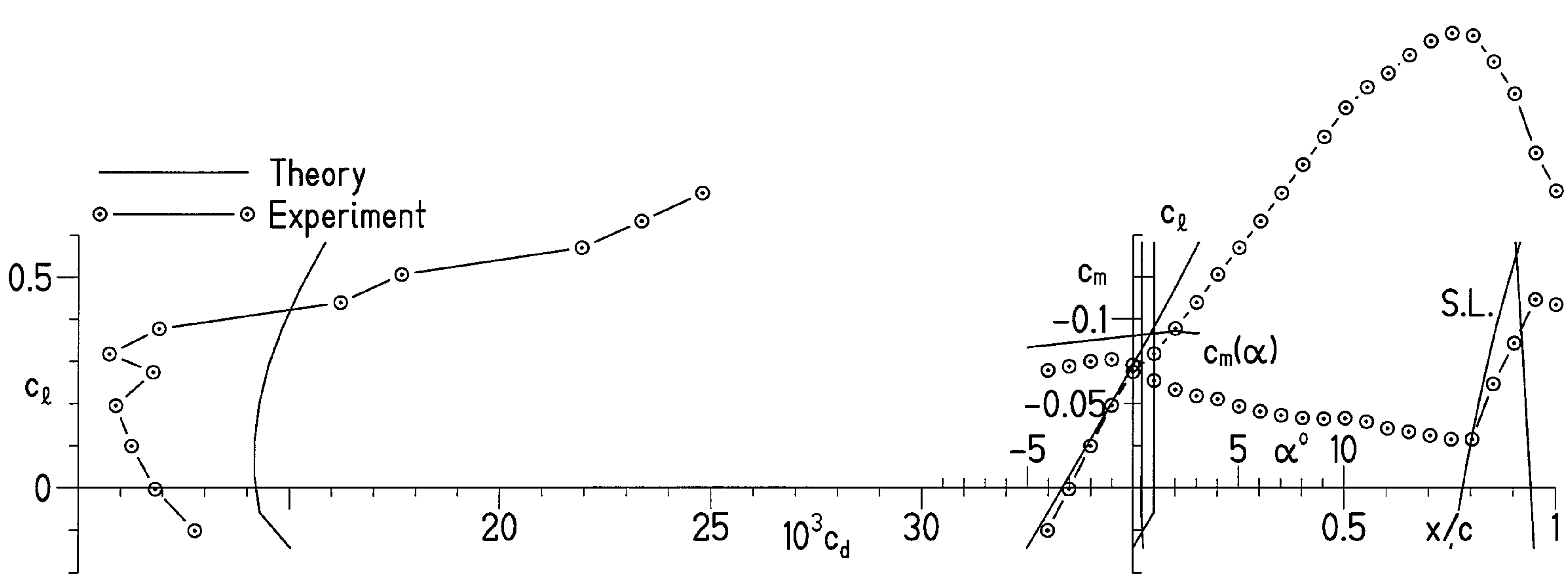
(d) $R = 4 \times 10^6$.

Figure 12.- Continued.



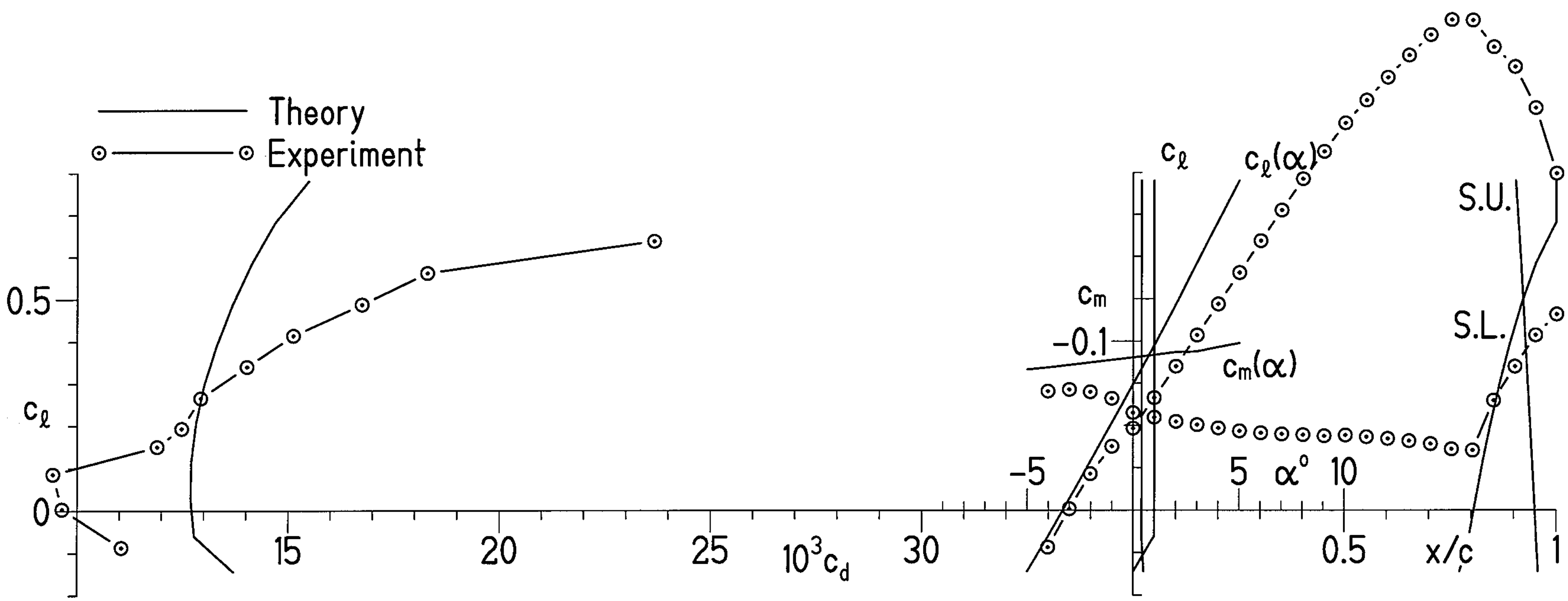
(e) $R = 6 \times 10^6$.

Figure 12.- Concluded.



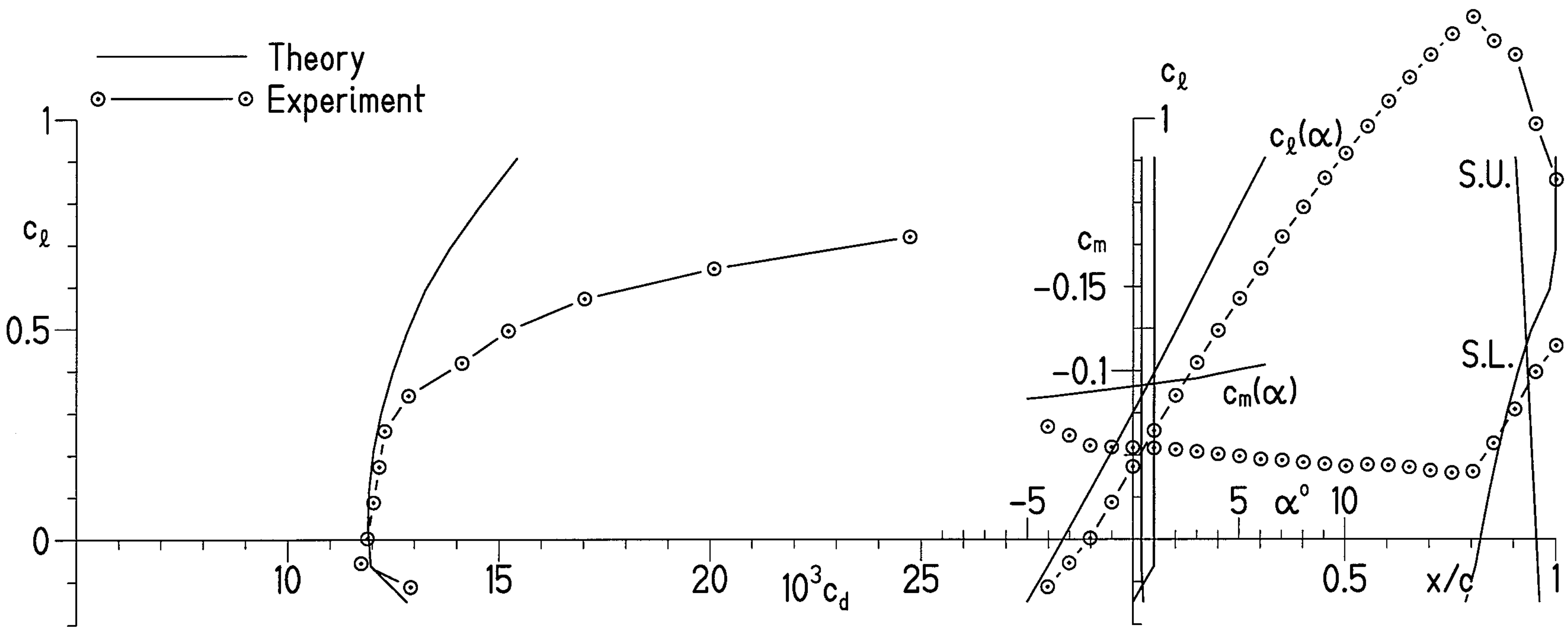
(a) $R = 1 \times 10^6$.

Figure 13.- Comparison of theoretical and experimental section characteristics with transition fixed.



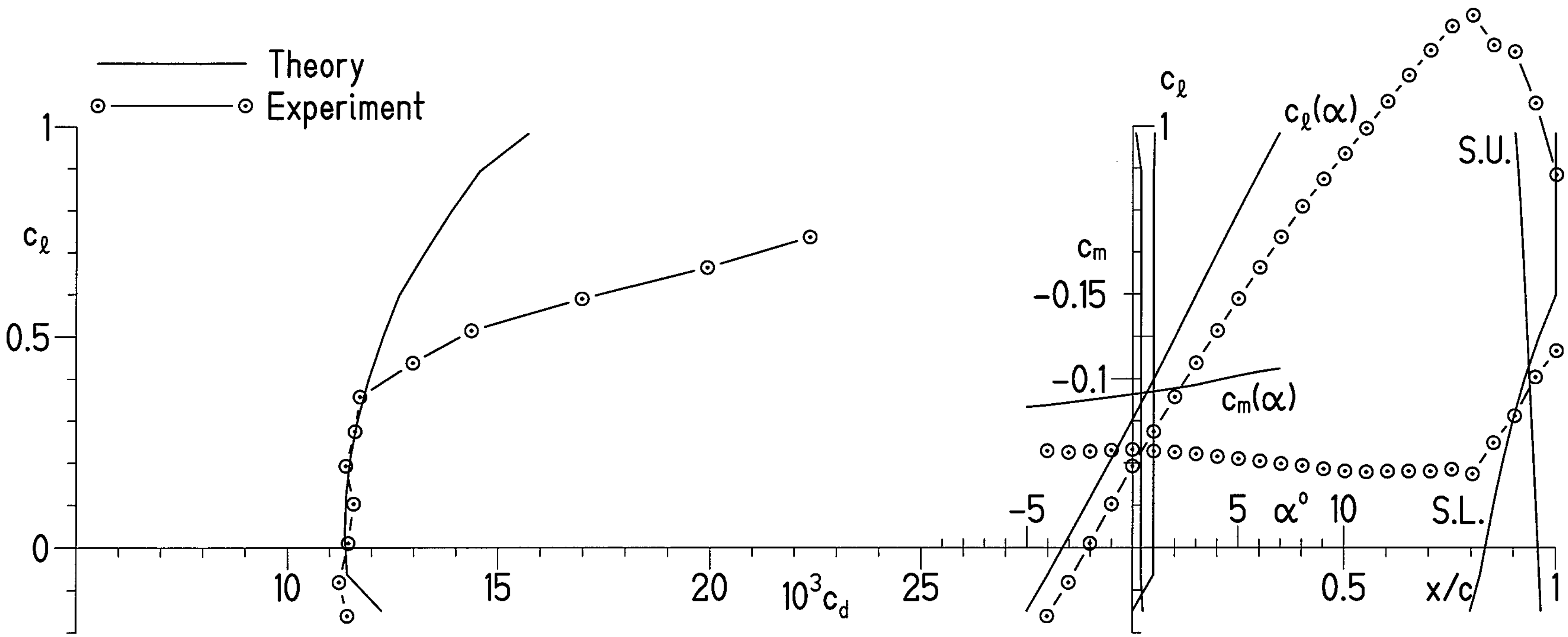
(b) $R = 2 \times 10^6$.

Figure 13.- Continued.



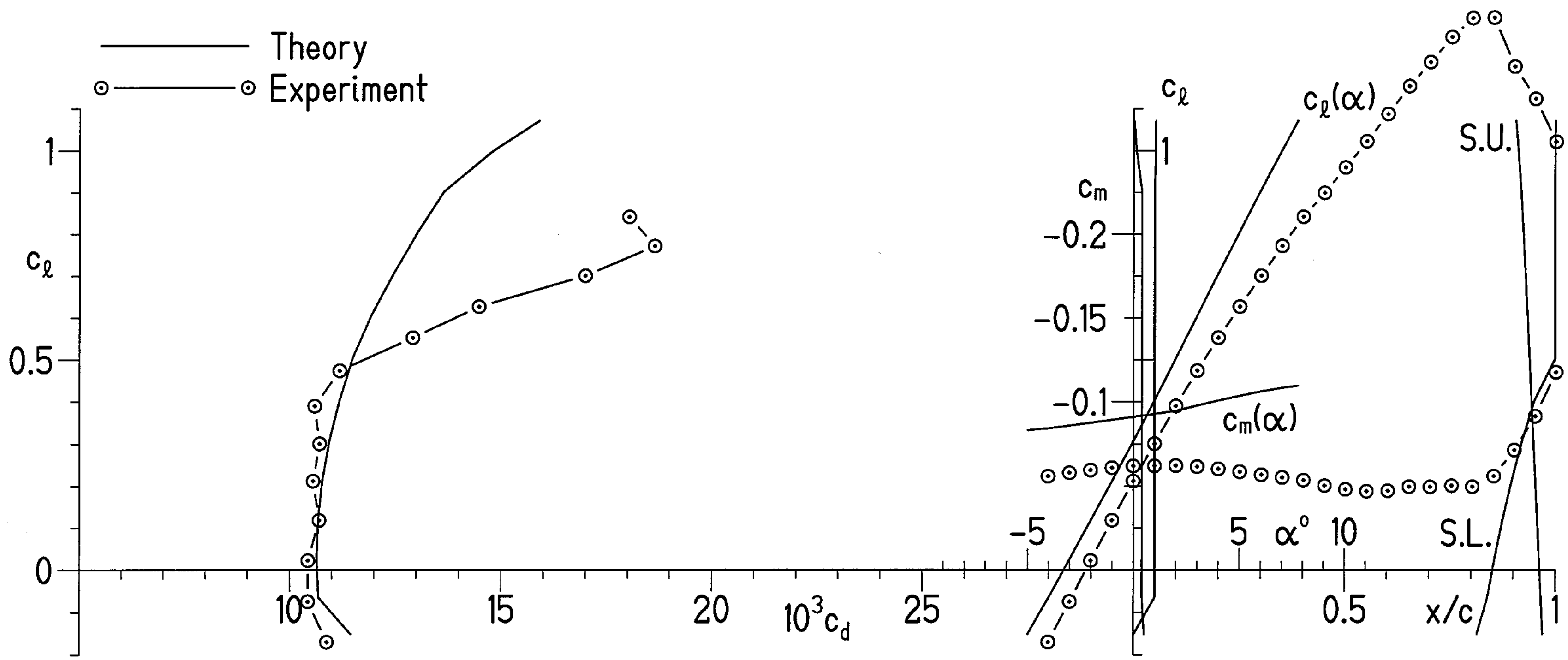
(c) $R = 3 \times 10^6$.

Figure 13.- Continued.



(d) $R = 4 \times 10^6$.

Figure 13.- Continued.



(e) $R = 6 \times 10^6$.

Figure 13.- Concluded.

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14. ABSTRACT *(Maximum 200 Words)*
A 21% - thick, natural-laminar-flow airfoil, the S827, for the 75% blade radial station of 40- to 50-meter, stall-regulated, horizontal-axis wind turbines has been designed and analyzed theoretically and verified experimentally in the NASA Langley Low-Turbulence Pressure Tunnel. The primary objective of restrained maximum lift has not been achieved, although the maximum lift is relatively insensitive to roughness, which meets the design goal. The airfoil exhibits a relatively docile stall, which meets the design goal. The primary objective of low profile drag has been achieved. The constraints on the pitching moment and the airfoil thickness have been satisfied. Comparisons of the theoretical and experimental results generally show good agreement with the exception of maximum lift, which is significantly underpredicted.

15. SUBJECT TERMS
airfoils; wind turbine; airfoil design; Pennsylvania State University; wind energy

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